TIME SERIES TESTS OF ENDOGENOUS GROWTH MODELS*

CHARLES I. JONES

According to endogenous growth theory, permanent changes in certain policy variables have permanent effects on the rate of economic growth. Empirically, however, U. S. growth rates exhibit no large persistent changes. Therefore, the determinants of long-run growth highlighted by a specific growth model must similarly exhibit no large persistent changes, or the persistent movement in these variables must be offsetting. Otherwise, the growth model is inconsistent with time series evidence. This paper argues that many AK-style models and R&D-based models of endogenous growth are rejected by this criterion. The rejection of the R&D-based models is particularly strong.

I. INTRODUCTION

A hallmark of the endogenous growth literature is that permanent changes in variables that are potentially affected by government policy lead to permanent changes in growth rates. This is the result in both the early "AK"-style growth models of Romer [1986, 1987], Lucas [1988], and Rebelo [1991], as well as in subsequent models focusing more explicitly on endogenous technological change by Romer [1990], Grossman and Helpman [1991a, 1991b] and Aghion and Howitt [1992]. This "growth effects" result stands in marked contrast to the neoclassical growth model proposed by Solow [1956], in which the presence of long-run growth depends crucially on exogenous technological progress. This paper argues that the prediction of long-run growth effects provides a simple, intuitive test of endogenous growth models in a time series context.

The literature review in Grossman and Helpman [1991a, 1991b] cites no fewer than ten potential determinants of long-run growth, including physical investment rates, human capital investment rates, export shares, inward orientation, the strength of property rights, government consumption, population growth, and regulatory pressure. Permanent changes in these variables, at least according to some endogenous growth model, should lead to permanent changes in growth rates. In OECD economies over the

last 40 years or so, many of these variables have exhibited large, persistent movements, generally in the "growth-increasing" direction. For instance, openness to international trade has increased since World War II among many OECD economies, as documented by Ben-David [1993]. Similarly, durables investment as a share of GDP has increased for most of these economies since 1950, as documented below. Average years of education per adult, educational spending as a share of GDP, literacy rates, and school enrollment rates have also increased.[1] One might expect to see increasing growth rates given this evidence and the predictions of endogenous growth theory.

In fact, growth rates of GDP per capita show little or no persistent increase in the post-World War II era for OECD economies; what change has occurred has been down rather than up. Two possibilities are suggested: either by some astonishing coincidence all of the movements in variables that can have permanent effects on growth rates have been offsetting, or the hallmark of the endogenous growth models, that permanent changes in policy variables have permanent effects on growth rates, is misleading.

Section II of this paper documents the lack of large persistent changes in the growth rate of U. S. GDP per capita over the last century and discusses how this result extends to the OECD for the postwar era. This section then proposes a simple time series test of endogenous growth models: the determinants of long-run growth highlighted by an endogenous growth model must, like growth rates, exhibit little persistent change, or their persistent movements must be offsetting.

Sections III and IV of the paper apply this test to the two classes of endogenous growth models present in the literature, the AK growth models of Romer [1987] and Rebelo [1991] among many others, and the R&D-based growth models of Romer [1990], Grossman and Helpman [1991], and Aghion and Howitt [1992].[2] Section III documents the presence of large, permanent movements in investment rates for many OECD economies and esti-

---

1. Data on education in the United States, for instance, shows an increase in education expenditure as a fraction of GNP from 4.8 percent in 1959 to 6.8 percent 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 education workforce. However, the average years of education for the population aged 25 and over in the United States rose from 9.3 years in 1950 to 12.6 years in 1986. (These data are taken from the *Digest of Education Statistics* [1988].
2. To ease exposition, I will refer to these as the Romer/GH/AH models.

mates that a permanent increase in the investment rate affects growth only over a relatively short horizon of eight to ten years, far from the infinite horizon predicted by AK models. Reinforcing other research testing the AK models such as Mankiw, Romer, and Weil [1992], this section concludes that the AK models do not provide a good description of growth in advanced economies.

Section IV then examines the most recent class of endogenous growth models, the R&D-based models that focus more explicitly on endogenizing technological change. This section argues that the presence of scale effects in the R&D-based growth models of Romer/GH/AH and others is obviously inconsistent with time series evidence. These models share the counterfactual prediction that a permanent increase in the *level* of resources devoted to R&D should lead to a permanent increase in growth rates. Empirically, measures such as the number of scientists and engineers engaged in R&D exhibit rapid exponential growth in sharp contrast to the apparent stationarity of growth rates. A brief discussion at the end of Section IV summarizes results in Jones [1995] that extend the R&D-based models to eliminate the prediction of scale effects. That paper shows that eliminating scale effects in a straightforward way also eliminates the hallmark of the endogenous growth literature: in the extended model, the long-run growth rate is invariant to conventional government policies.

II. TIME SERIES PROPERTIES OF GROWTH RATES

Consider the following simple exercise.[3] 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 United States 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 rough indicator of the importance of the positive permanent movements in growth rates.

Figure I displays the somewhat surprising result of this exercise in light of the discussion of endogenous growth theory in the Introduction: the prediction is off by only about 5 percent of GDP![4] Furthermore, the prediction *overestimates* per capita GDP

---

3. I am indebted to David Weil (who in turn credits Lawrence Summers) for suggesting this method of presentation.
4. The Data Appendix at the end of the paper discusses the data used here and throughout the paper.
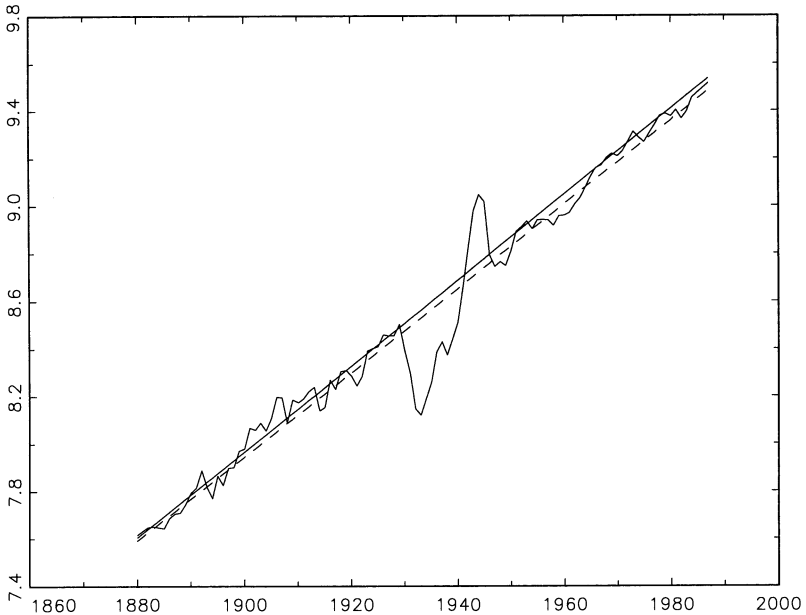
FIGURE I
Per Capita GDP in the United States, 1880–1987 (Natural logarithm)
    Source. The data are from Maddison [1982, 1989] as compiled by Bernard
[1991]. The solid trend line represents the time trend calculated using data only
from 1880 to 1929. The dashed line is the trend for the entire sample.

rather than underestimates it, indicating that the average growth
rate between 1880 and 1929 (1.81 percent annually) was actually
slightly larger than that between 1929 and 1987 (1.75 percent
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 percent, but the difference from the earlier
period is statistically insignificant.

    As is clear from the figure, a simple linear trend fits per capita
GDP (in logs) extremely well. The magnitude of the permanent
increases in growth rates since 1880 is sufficiently small that the
level of output is fit well by a growth process with a constant mean.
This casual observation is confirmed rigorously by several empiri-
cal methods reported in Table I. A time trend test, an augmented
Dickey-Fuller (ADF) [1979] test, testing for a single endogenously
chosen mean shift, and a simple difference in means test omitting
the Great Depression all support the hypothesis that U. S. growth
rates are well described by a process with a constant mean and very

TABLE I
TIME SERIES PROPERTIES OF U. S. GROWTH RATES 1880–1987

	Coefficient	Standard error	Test-statistic
1. Time trend[a]	0.0013	(0.0134)	0.10
2. Augmented Dickey-Fuller test[b]	0.246	· · ·	−7.98
3. Endogenous mean shift[c]	1.633 (1933)	· · ·	2.14
4. Difference in means: 1880–1929 vs. 1950–1987[d]	0.096	(0.893)	0.11

a. 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 error and tests $\beta = 0$. Note that growth rates are multiplied by 100, here and throughout the paper.
b. 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 Schwartz information criteria. The test-statistic tests the null hypothesis of $\rho = 1$. Critical values from Fuller [1976] for the 1 percent significance level are given below:

$$\begin{array}{ll} T = 25 & -3.75 \\ T = 50 & -3.58 \\ T = 100 & -3.51 \end{array}$$

c. 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 percent 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 percent significance level is 6.17. The coefficient and value of T^* corresponding to the max Wald statistic are also reported.
d. 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.

little persistence. The implication for growth models is rather stark: either nothing in the U. S. experience since 1880 has had a large, persistent effect on the growth rate, or whatever persistent effects have occurred have miraculously been offsetting.

Of course, these results must be qualified by a consideration of the standard errors associated with the point estimates in Table I. For example, although the difference in mean growth rate between 1880–1929 and 1950–1987 is less than a tenth of a percentage point, the 95 percent confidence interval for this estimate is $(-1.69, +1.88)$. That is, it includes the possibility that growth rates have increased by 1.88 percentage points across the two periods. A similar lack of precision muddies the interpretation of the time trend in growth rates. Although the point estimate implies a small and insignificant increase of only 0.013 percentage points per decade, the 95 percent confidence interval corresponds to

TABLE II
TIME SERIES PROPERTIES OF SELECT OECD GROWTH RATES

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

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

(−0.25,+0.28) percentage points per decade. Fortunately, we will still be able to draw fairly strong conclusions about endogenous growth models later in the paper, despite these relatively large standard errors.

Table II attempts to extend this analysis to growth rates for a sample of fourteen additional advanced OECD economies.[5] The

5. These additional countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Norway, Sweden, and the United Kingdom. The starting date of 1900 is chosen as in Bernard [1991] to minimize the problems associated with border changes in these countries.

sample is restricted to advanced countries because 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 clear that they help us to understand the former.

The picture that emerges for the growth experience of the OECD sample is mixed. ADF tests strongly reject the null hypothesis of a unit root in growth rates over the period 1900–1987 and imply a first-order autoregressive root that is typically less than 0.3. 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. The countries with significant mean shifts are Australia, Austria, Germany, Italy, Japan, and the United Kingdom. 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 was 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.

Figure II illustrates this point graphically by comparing U. S. and Japanese growth rates for 1900 to 1987. U. S. growth rates appear to fluctuate around a constant mean for the entire period. In contrast, Japanese growth rates apparently fluctuate around a constant mean until World War II, but after the war they jump upward and then decline slowly over subsequent years. The change in the stochastic properties associated with World War II suggests 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 call into question the implicit prediction of many endogenous growth models that growth rates should exhibit large permanent increases. Using time series data over a very long horizon for the United States, tests reveal that the growth rate of GDP per capita is well characterized as a process with little persistence and a constant mean. This characterization has important implications for empirical work. For instance, one might be tempted to decompose growth and openness into perma-
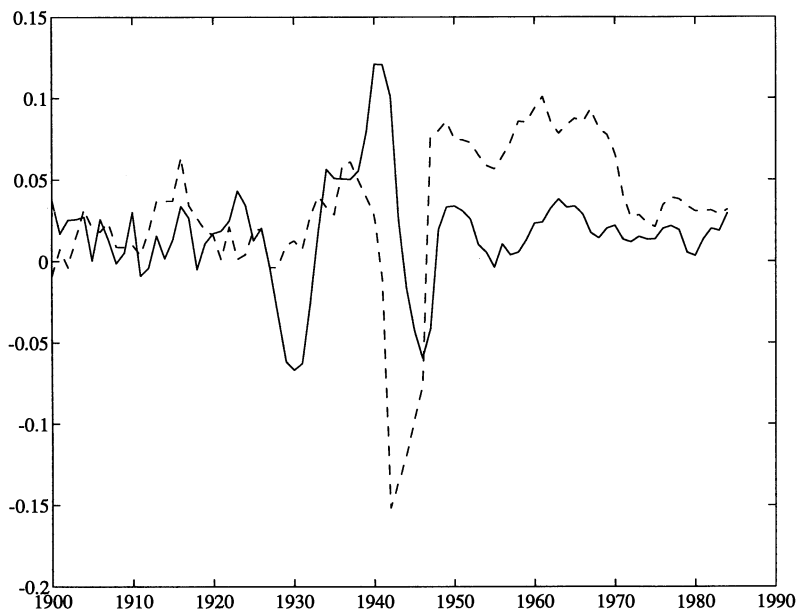
FIGURE II
Annual Growth Rates for the United States (solid) and Japan (dashed), 1900–1987
    Source. Five-year moving averages are plotted. The data are from Maddison [1982, 1989] as compiled by Bernard [1991].

nent and transitory components to examine the extent to which permanent movements in growth are due to permanent movements in openness. The evidence presented above indicates that growth rates exhibit no large 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 exhibit no large persistent movements, or

    (b) some other variable (or variables) must also have persistent effects on growth that offset the movements of X in a way that is determined by the endogenous growth model.

This restriction applies directly to the United States. 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.

    This restriction provides a general framework for testing

endogenous growth models. The remainder of this paper is devoted to applying this framework to the two major strands of endogenous growth models that have been proposed in the literature, the AK models and the R&D-based models.

III. Tests of AK Models of Endogenous Growth

The first wave of endogenous growth models focused on constant returns to a sufficiently broad definition of capital as the device for generating endogenous growth. Models in this class, which I refer to as AK models, include Romer [1987], Rebelo [1987, 1991], Barro [1991b], and Benhabib and Jovanovic [1991]. Cross-sectional empirical work such as Barro [1991a] and Mankiw, Romer, and Weil [1992] has generally been viewed as inconsistent with the AK models, motivating a shift in the literature to the other class of growth models considered in this paper, the R&D-based models. This section employs the time series test developed above to provide time series evidence against the AK models. Together with the cross-sectional empirical literature, this evidence suggests that the AK models may provide a misleading view of long-run growth.

Consider a simple growth model with a constant returns production technology involving two capital goods, physical capital k and human capital h. The model is given by

$$(1) \qquad \max_{i_t^k, i_t^h} \int_{t=0}^{\infty} e^{-\rho t} u(c_t) \mathrm{d}t$$

subject to

$$c_t = (1 - i_t^k - i_t^h) y_t$$
$$y_t = A k_t^{\alpha} h_t^{1-\alpha}$$
$$\dot{k}_t = i_t^k y_t - \delta k_t$$
$$\dot{h}_t = i_t^h y_t - \delta h_t,$$

where the notation is standard: $u(\cdot)$ is a CRRA utility function with intertemporal elasticity of substitution σ, c is consumption, y is output, δ is the rate of depreciation (assumed to be the same for both types of capital), ρ is the rate of time preference, and i^k and i^h are the investment rates in physical and human capital, respectively. Production in this model exhibits constant returns to the accumulable factors, which will generate endogenous growth.

Solving the problem in equation (1), it is straightforward to

show that the ratio h/k (which we will define as ψ) is constant and equal to $(1 - \alpha)/\alpha$. Since there are no adjustment costs in this model, the economy will instantaneously adjust the initial amounts of k and h so that this ratio is achieved. In the presence of adjustment costs, the results in this section would presumably hold along a balanced growth path. Thus, although this model allows the second capital good to accumulate endogenously, in fact the two types of capital accumulate in lockstep. Using this fact, we can rewrite the production function in terms of a new "reduced-form" production technology:

$$(2) \qquad\qquad y_t = \tilde{A}k_t, \qquad \tilde{A} = A\psi^{1-\alpha}.$$

Equation (2) looks exactly like the standard AK production technology in which the parameter multiplying the capital stock is a constant.[6]

   Now consider the steady state relationship between the growth rate and the investment rate. We can take logs and differentiate (2) to find

$$(3) \qquad\qquad g_y = -\delta + \tilde{A}i^k.$$

That is, the steady state growth rate of output, g_y, 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.

   At this point, it should be noted that the model in equation (1) has been employed explicitly in numerous recent growth papers, although the production function is generally written as some variant of (2). These include Romer [1987], Rebelo [1991], Barro [1991b], and Easterly [1991], among others. The formulation in (1) is perhaps more appealing intuitively than the common AK structure of (2) because it recognizes explicitly that technology/ human capital plays an important role in production. The result of

   6. The requirement that the A parameter be constant (or at least stationary) in the standard AK production function can be seen as a simple result of the time series test developed earlier. It is easy to show that the growth rate of output in an AK framework is a monotonic function of the level of A. Then, if A contains some exogenous technological progress that is omitted from the model so that A grows exogenously over time, the growth rate of the economy should be growing exponentially, an implication clearly at odds with the stationarity restriction. The same point implies that one must be careful about how a growing labor force affects production in the simplest AK models.

this model is that the two types of capital move together, and this feature is likely to be robust to a number of changes and interpretations of the two-types model. Therefore, time series tests of the restriction given in equation (3) 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 human capital or technology and the accumulation of physical capital must be modeled more carefully.

A. Time Series Evidence on Investment Rates

The prediction that a permanent increase in the investment rate generates a permanent increase in growth is a key feature of the AK-style models of endogenous growth. As discussed earlier, growth rates for the OECD sample show little or no persistent increase for the period 1950 to 1988, although for some countries the growth rates exhibit a downward trend. The restriction imposed by equation (3) will be violated, then, if investment rates contain important persistent upward movements.

In fact, investment rates for many of the advanced OECD countries exhibit a strong positive trend in the postwar period. Moreover, the trend is strengthened if one follows De Long and Summers [1991] and Jones [1994] and focuses on producer durables investment. The basic point is made in Table III which compares average investment shares between the early 1950s and the late 1980s, for five countries.

Table IV documents the time series properties of investment rates more formally in the fifteen-country sample using augmented Dickey-Fuller tests and tests for a deterministic time trend.[7] For total gross investment as a share of GDP, evidence of nonstationarity can be found in Table IV for roughly one-third to one-half of the sample. The Dickey-Fuller tests (with admittedly low power) cannot reject a unit root null at the 10 percent level for fourteen of the fifteen economies. (Interestingly, the exception is the United States.) Moreover, several of the countries, including the United States, exhibit highly significant and positive time trends for the total investment rate, as shown by simple trend tests.

7. Strictly speaking, of course, 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. Based on equation (3), 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 (1). Therefore, the ADF tests are in fact valid tests of that model.

TABLE III
AVERAGE INVESTMENT SHARES OF GDP (PERCENT)

	France	Germany	Japan	United Kingdom	United States
Total investment					
1950—1954	18.4	26.1	16.1	12.1	16.5
1955—1959	20.8	29.2	19.0	14.3	16.0
1960—1964	24.0	30.3	26.8	16.7	15.7
1965—1969	26.9	29.5	30.7	18.9	16.9
1970—1974	29.5	28.7	36.5	19.6	17.2
1975—1979	26.4	24.7	32.5	18.7	17.4
1980—1984	24.2	23.9	29.4	16.2	17.3
1985—1988	23.7	23.6	29.6	18.8	18.1
Producer durables investment					
1950—1954	4.3	4.8	3.4	4.8	4.4
1955—1959	5.1	5.5	3.8	5.5	4.3
1960—1964	6.3	6.8	5.6	6.0	4.2
1965—1969	6.9	6.9	6.0	6.6	5.2
1970—1974	8.1	7.8	7.4	6.9	5.4
1975—1979	8.0	7.3	6.4	6.9	5.9
1980—1984	7.9	7.6	7.5	6.6	6.2
1985—1988	8.0	8.1	9.8	7.5	7.2

Source. Summers and Heston [1991] and unpublished data courtesy of Robert Summers.

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. 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.[8]

Another important criticism of the use of total investment data is suggested by the recent research of De Long and Summers [1991] and Jones [1994]. These authors argue that machinery investment is the crucial component of investment for explaining growth performance: in cross-country regressions, machinery in-

---

8. The trend in investment rates for the United States 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 are themselves subject to criticism. For example, much depreciation in practice results from obsolescence rather than physical depletion. See Scott [1992] for this criticism.

TABLE IV
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	−0.083	0.805	0.030
	(−2.27)	(−1.50)	(−1.71)	(1.60)
Austria	0.748	0.279	0.420	0.071
	(−1.72)	(4.46)***	(−3.59)*	(3.82)***
Belgium	0.794	0.034	· · ·	· · ·
	(−2.06)	(0.41)		
Canada	0.531	0.083	0.810	0.077
	(−2.95)	(1.91)*	(−1.71)	(3.85)***
Denmark	0.882	−0.018	0.651	0.096
	(−1.41)	(−0.11)	(−2.66)	(5.55)***
Finland	0.618	−0.068	0.677	0.042
	(−2.57)	(−0.69)	(−2.84)	(1.22)
France	0.916	0.166	0.902	0.113
	(−1.17)	(1.68)	(−1.28)	(5.69)***
Germany	0.769	−0.146	0.659	0.086
	(−2.27)	(−2.12)**	(−3.48)*	(6.18)***
Italy	0.797	−0.095	0.374	0.037
	(−2.53)	(−0.85)	(−4.30)**	(3.69)***
Japan	0.899	0.426	0.820	0.159
	(−1.41)	(2.84)***	(−1.56)	(7.76)***
Netherlands	0.823	−0.140	0.854	0.008
	(−2.21)	(−1.36)	(−1.69)	(0.21)
Norway	0.573	−0.036	0.666	−0.155
	(−3.02)	(−0.64)	(−2.73)	(−2.62)**
Sweden	0.819	−0.033	0.443	0.052
	(−1.82)	(−0.43)	(−3.61)**	(6.08)***
United Kingdom	0.723	0.158	0.605	0.066
	(−2.62)	(2.71)**	(−2.73)	(5.48)***
United States	0.028	0.068	0.712	0.080
	(−5.74)***	(2.18)**	(−2.43)	(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. The Time trend columns report the coefficient on a time trend in a simple regression, as in Table I.

vestment 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 ex-tremely 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 IV report the ADF tests and time trend tests for the producer durable investment rate.[9] Using producer durables investment also addresses the concern with differences in depreciation rates since the primary difference is between structures and equipment. The results 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.

The problem with the AK models is easily summarized by returning to Table III. Investment rates have increased substantially in the postwar era. Total investment rates have increased by several percentage points for a number of countries. More convincingly, though, producer durable investment rates have increased by about three percentage points—from just over 4 percent of GDP to more than 7 percent of GDP—for France, Germany, the United Kingdom, and the United States. In Japan, the rise is even larger, from about 3.5 percent of GDP to more than 9 percent. Despite these large movements in investment rates, growth rates have fallen, if anything, over the postwar era.

Taken together, these results can be interpreted as fairly strong support for the view that investment rates contain large, persistent movements for most of the advanced OECD countries. Furthermore, it is difficult to think of any omitted variable 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 postwar period. Also, energy price shocks will

---

9. Producer durable investment differs from machinery investment only by the inclusion of transportation equipment in the former. Since the cross-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.

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 inflation for the period 1950–1988.[10] This failure of this time series test indicates that the model of equation (1) is rejected by the data, suggesting that the AK models do not provide a good description of the driving forces behind growth in developed countries.

B. The Horizon over Which Investment Affects Growth

The evidence above is compelling but does not take full advantage of the restriction imposed by equation (3). A natural procedure for testing the AK models is to test this restriction explicitly, considering the joint time series behavior of investment and growth. 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 AK models suggests a dynamic relationship such as

$$(4) \qquad g_t = A(L)g_{t-1} + B(L)i_t + \epsilon_t,$$

where $A(L)$ and $B(L)$ are two lag polynomials with roots outside the unit circle. This equation can be rewritten as

$$(5) \qquad g_t = A(L)g_{t-1} + B(1)i_t + C(L)\Delta i_t + \epsilon_t,$$

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

$$(6) \qquad c_k = - \sum_{i=k+1}^{p} b_i, \qquad k = 1, \ldots, p - 1.$$

The restriction in equation (3) can be interpreted in this dynamic relationship as the requirement that $B(1) > 0$, 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. Not surprisingly, given the evidence above, the empirical estimation of equation (5) provides no evidence for $B(1) > 0$, in results not reported here.[11]

---

10. If 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* [1990].)

11. In fact, several estimates produce B(1) significantly less than zero, reflecting a positive trend in investment and a negative trend in growth. Detailed results are available from the author upon request. The endogeneity of investment is dealt with in these tests using the methods described below.

This result together with those in the previous section provides strong evidence that the key restriction imposed by AK 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 25 or 30 years. In this case, although the AK 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 AK 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 impose the restriction $B(1) = 0$ above and consider the following equation:

$$(7) \qquad g_{it} = \alpha_i + \beta_i t_i + A(L)g_{it-1} + C(L)\Delta i_{it} + \epsilon_{it}.$$

This equation augments equation (5) with 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 V reports OLS estimates of equation (7) as well as the dynamic response of growth rates to a permanent one-percentage-point increase in the investment rate, for both total investment and durable investment.[12] Figure III graphs these dynamic responses together with one-standard-error bands calculated numerically using the delta method. Notice that the dynamic responses calculated using OLS will be biased because of the endogeneity of investment. 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

---

12. 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.

TABLE V
DYNAMIC RESPONSE OF GROWTH RATES AND OUTPUT TO A ONE-PERCENTAGE-POINT
PERMANENT INCREASE IN THE INVESTMENT RATE

Period (year)	Total investment		Producer durables investment	
	OLS dynamic response	OLS cumulative response	OLS dynamic response	OLS cumulative response
0	0.802	0.802	1.020	1.020
1	−0.013	0.789	0.167	1.186
2	0.030	0.819	−0.222	0.965
3	0.055	0.874	0.263	1.228
4	0.081	0.955	−0.012	1.216
5	0.133	1.088	−0.015	1.201
6	0.008	1.096	−0.026	1.175
7	−0.008	1.088	0.009	1.184
8	−0.014	1.074	0.005	1.189
9	−0.007	1.067	0.001	1.190
10	−0.009	1.058	−0.002	1.188
15	0.001	1.062	−0.000	1.188
20	−0.000	1.061	−0.000	1.188

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. For the specification with total investment, five lags of both growth and investment are used. For the specification with producer durables investment, four lags of growth and investment are used. The results are robust to the choice of lag length.

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. 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.

Table V 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:

$$y = k^\alpha, \quad \alpha < 1$$
$$\dot{k} = iy - (n + g + \delta)k,$$

(8)

Total Investment
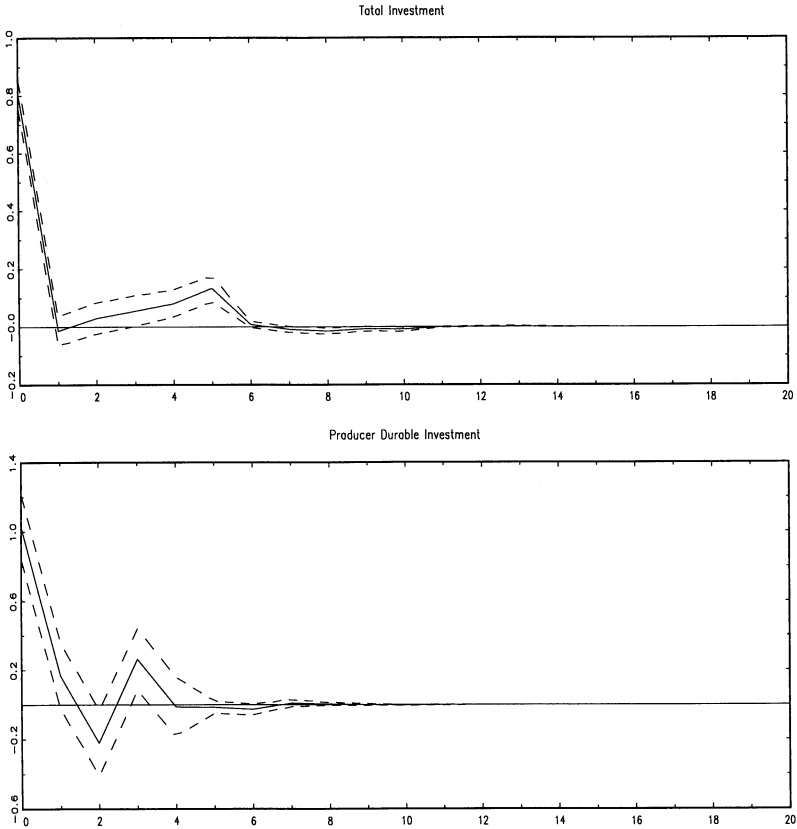

Producer Durable Investment

FIGURE III
Dynamic Response of Growth Rates to a Permanent One-Percentage-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 V.

where the notation is the same as in the previous section, except
that n and g are population growth and exogenous productivity
growth and the output and capital variables are defined per unit of
effective labor. In this model, it is straightforward to show that

$$(9) \qquad \frac{\partial \ln y^{ss}}{\partial i} = \frac{\alpha}{1 - \alpha} \frac{1}{i},$$

where the partial derivative is used to denote the fact that the level
of technology is held constant. To calibrate this model, let us

assume that $i = 0.25$, the average value of the investment rate from our OECD sample. For $\alpha = 0.25$, equation (10) 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 $\alpha = 0.33$, the long-run effect is 2.00 percent. The estimates in Table V from the OLS results are then plausible, but perhaps slightly low.[13]

Appendix A extends this analysis to account for the potential endogeneity of investment using a "bounds identification" technique. The extended results uniformly indicate that the horizon over which a permanent shock to investment has effects on growth is less than eight years.

The results refine the evidence presented in the cross-section studies of De Long and Summers [1991] and Jones [1994]. Those studies 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 (25-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 for only short- to medium-term horizons. The discrepancy between the cross-section and the time series results is potentially accounted for by the positive trend in durable investment rates over the last 25 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 25 years, then, could easily raise the average growth rate over this horizon, but such an increase will not be permanent.[14]

This relatively short horizon is a sharp criticism of the AK 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 also it appears that the horizon over

---

13. This 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 United States 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.

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

which that effect occurs is sufficiently short to make the predictions of the AK models misleading.

IV. TESTS OF R&D-BASED GROWTH MODELS

A. Theory

In part because of dissatisfaction with the empirical performance of the AK models, the endogenous growth literature has shifted to models that explain long-run growth by focusing on technological progress and R&D, such as Romer [1990], Grossman and Helpman [1991a, 1991b] and Aghion and Howitt [1992]. In these models, technological progress results from the search for innovations, a search that is undertaken by profit-maximizing individuals. The discovery of an innovation raises productivity, and such discoveries are ultimately the source of long-term growth.

While the substance of these models is both detailed and complicated, many of their key implications can be seen by considering the following "reduced-form" model:[15]

(10) $$Y = K^{1-\alpha}(AL_Y)^\alpha$$

(11) $$\dot{A}/A = \delta L_A,$$

where Y is output, A is productivity or knowledge, and K is capital.[16] Labor is used in either of two activities, the production of output (L_Y) or the search for 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.[17]

Equation (10) is a standard production function with Harrod-neutral technological progress. 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; doubling the stock of knowledge as well would lead

---

15. This simplification suppresses several of the interesting theoretical contributions by Romer/GH/AH, in particular the way in which the increasing returns of the production function is reconciled with a decentralized specification.

16. Notice that δ is used in this section to parameterize the efficiency of R&D rather than as a depreciation rate.

17. Romer [1990] makes the distinction between skilled labor H and unskilled labor L and assumes 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 that model 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.

to more than a doubling of output. For example, once Steve Jobs and Steve Wozniak discovered how to combine labor and circuit boards to produce a personal computer, 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, computer technicians, and a larger garage 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 [1991b]). However, the reduced form of these models invariably takes a form similar to that in equation (10).

The R&D equation in (11) is the heart of the Romer/GH/AH models and relates the labor engaged in R&D to the growth rate of knowledge. 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,[18] and these growth rates will be equal to the growth rate of total factor productivity as is evident when equation (10) is written in per capita terms and log-differentiated. The steady state growth rate for this economy is then given by

$$(12) \qquad g_y = g_A = g \equiv \delta s^* L,$$

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 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.

18. That capital and output grow at the same rate requires more discussion. Intuitively, 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 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.

Equation (12) 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, holding fixed s^*.[19] 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 technologically distinct 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 that these economies avoid the duplication of effort in R&D and focus on different innovations. Issues of technology transfer complicate the interpretation of cross-sectional evidence on scale effects, but the time series restriction outlined earlier provides a natural test of this implication.

B. Time Series Evidence

The implication of scale effects is easily rejected by the lack of persistent increase in growth rates: according to the Romer/ GH/AH models, the exponential trend in the level of the labor force should lead to an exponential trend in per capita growth rates.[20] Moreover, it is much more difficult to think of any variable(s) that could offset the exponential scale effect. To preserve the AK models, we require some variable to offset modest increases in investment rates. To preserve the R&D-based models, though, we require some variable to offset exponential increases in the level of resources devoted to R&D.

The intuition behind this argument carries through in more careful analysis. Consider the R&D equation in (11). This equation can be interpreted as saying that total factor productivity growth is proportional to L_A because the stock of knowledge, A, is also a Harrod-neutral productivity term. By focusing on (11) explicitly, we can pinpoint the problem in the R&D-based models and provide a test that is robust to issues such as transition dynamics.

To measure L_A, Figure IV graphs the number of scientists and engineers engaged in R&D for France, Germany, and Japan since 1965, and for the United States since 1950. For each country, this measure of L_A shows a very strong upward trend. Since 1950, for

19. In fact, s^* also rises in response to an increase in the size of the labor force reflecting a rise in the return to R&D.
20. The (log) level of the labor force exhibits a strong positive trend over the period 1950–1988 and is well described as a unit root process with positive drift for the OECD economies.
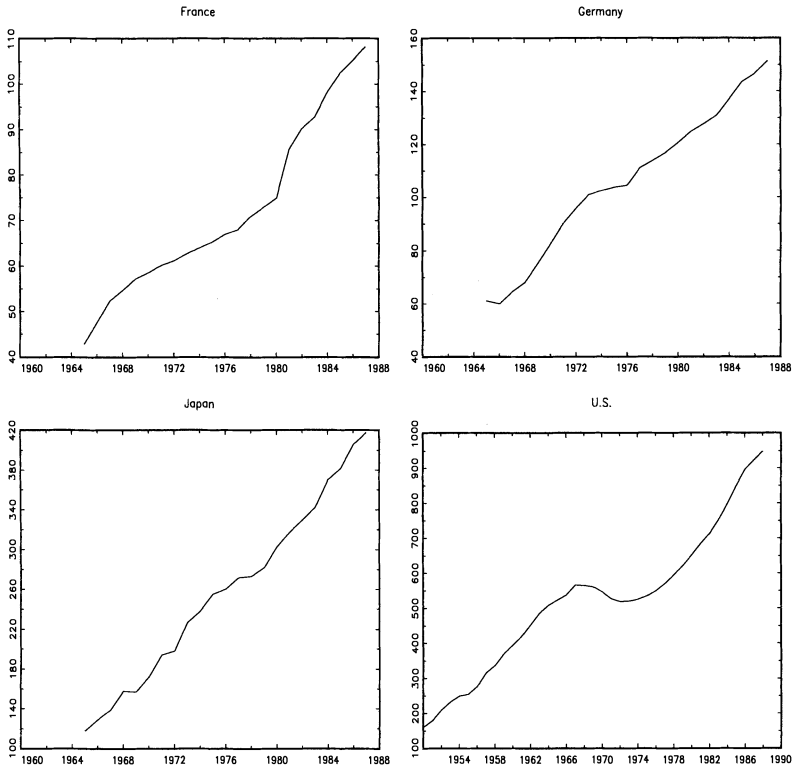
FIGURE IV
Scientists and Engineers Engaged in R&D (1000s)
Source. NSF Science and Engineering Indicators 1989 and Bureau of the Census (various).

instance, the number of scientists and engineers engaged in R&D in the United States has grown from less than 200,000 to almost one million, a more than five-fold increase. 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 percent in just over two decades. If instead the resources devoted to R&D are measured as real R&D expenditure, the figure looks very similar.

Figure V completes the analysis of the R&D equation by plotting total factor productivity growth rates for France, Germany, Japan, and the United States. Negative trends are visible for TFP growth in France and Japan, while no distinct trend is evident
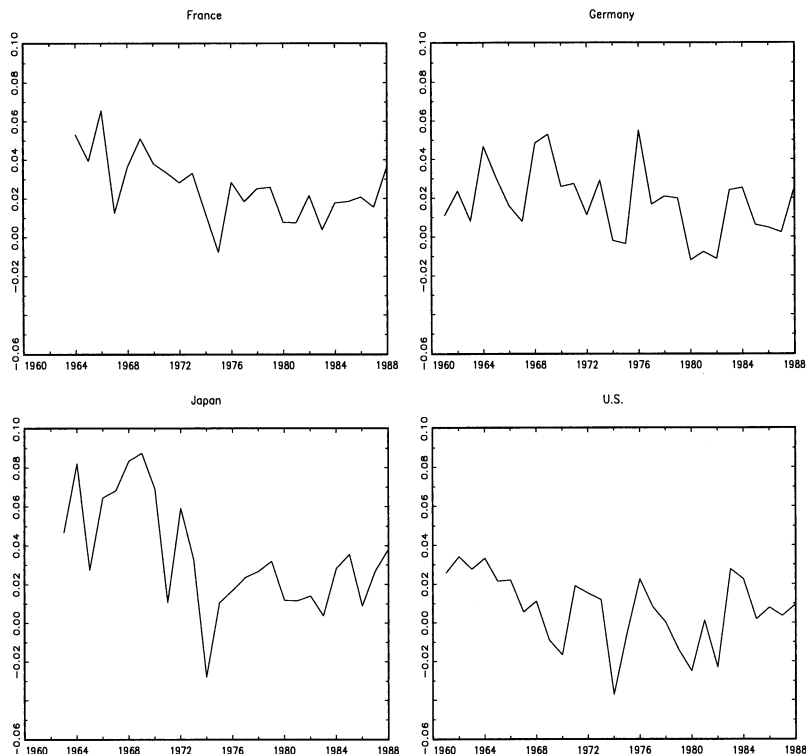
FIGURE V
Aggregate Total Factor Productivity Growth
Source. OECD Department of Economics and Statistics Analytic Database.
Data provided by Steven Englander.

for TFP growth in Germany and in the United States.[21] The R&D
equation central to the models of Romer/GH/AH, then, violates
the time series test proposed earlier: TFP growth exhibits little or
no persistent increase, and even has a negative trend for some
countries, while the measures of L_A exhibit strong exponential
growth. It should be obvious that these results can be supported
more rigorously.[22]

21. The point estimates of time trend coefficients for TFP growth are
uniformly negative, though only significant for France and Japan.
22. For example, a regression of TFP growth on the L_A variable, either with or
without lags, yields either a negative or zero long run response, depending on the
specification.

One concern that deserves further mention is the appropriateness of the country as the unit of observation. 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 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 positive exponential 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.

The models of Romer [1990], Grossman and Helpman [1991a, 1991b] and Aghion and Howitt [1992], are rejected easily using the time series test proposed in this paper. The models posit that the growth rates of per capita output and total factor productivity should be increasing with the level of resources devoted to R&D, which is wildly at odds with empirical evidence.

C. Discussion

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 a continual exogenous decline in productivity—a negative growth rate for the Solow residual—but this type of ad hoc argument is intellectually unpleasant.

Apart from the prediction of intertemporal scale effects, the R&D-based growth models are intuitively very appealing. Growth arises in the models as a result of innovation by rational, profit-maximizing agents. Because of this intuitive appeal, it is desirable to find a way to maintain the basic structure of these models while eliminating the prediction of scale effects. Jones [1995] examines one alternative model in detail, and the key argument there can be summarized as a restatement of a concept that is already familiar from the AK literature.

The R&D equation has an AK structure:

$$(13) \qquad \dot{A} = \delta L_A A,$$

i.e., the returns to accumulable inputs is equal to unity, which is

fundamentally why these models generate endogenous growth. One interpretation of the results obtained by applying the stationarity restriction is that the returns to accumulable inputs must be less than one. The implication of this is well-known, but worth repeating in the context of the R&D-based models. Consider the augmented R&D equation,

$$(14) \qquad \dot{A} = \delta L_A A^\phi,$$

where $\phi < 1$ is considered. Dividing both sides by A,

$$(15) \qquad \dot{A}/A = \delta(L_A/A^{1-\phi}).$$

In steady state the growth rate of A will be constant, by definition, so that the numerator and the denominator of the right-hand side of (15) must grow at the same rate. In fact, this ties down the growth rate of A: it is just $1/(1 - \phi)$ multiplied by the growth rate of L_A. But in steady state, the growth rate of the number of scientists can be no greater than the rate of population growth. Together with the production function given by equation (10), this implies that

$$(16) \qquad g_y = g_A = n/(1 - \phi).$$

That is, output per capita and all the usual variables grow at a rate determined by the rate of population growth and the parameter ϕ. With $\phi = 1$, no steady state growth path exists in the presence of population growth—growth is explosive; but with $\phi < 1$, the rate of population growth is a key determinant of per capita growth. This is analogous to a result associated with the Arrow [1962] learning-by-doing model with increasing but less than unitary returns to the accumulable factors.[23]

Jones [1995] provides a conceptual motivation for the R&D equation with $\phi < 1$ and examines the implications of this equation for growth and welfare in a Romer-style model. The underlying micro structure of Romer [1990] is virtually unchanged: growth still arises in the model because profit-maximizing agents undertake R&D in seach of innovations. However, in salvaging the micro structure, the hallmark of the endogenous growth literature is lost. Conventional government policies such as subsidies to R&D or to capital accumulation have no long-run

---

23. Kremer [1993] shows that a model like this one is consistent with the behavior of population over the course of human history.

growth effects in the model with $\phi < 1$. As in the Solow model, these policies affect the growth rate only along the transition path, producing level effects but not growth effects.

V. CONCLUSION

This paper uses the lack of large, persistent upward movements in growth rates to propose a general method for testing endogenous growth models. If we characterize endogenous growth theory by the prediction that permanent changes in policy variables lead to permanent changes in growth, then this lack of persistent change in growth rates imposes a strong restriction on these models: either the variables that have permanent effects on growth exhibit little persistent change, or somewhat miraculously the movements in these variables have been offsetting.

This test provides evidence against both classes of models in the endogenous growth literature, the AK models and the R&D-based models. With respect to the AK models, empirical estimates suggest that a permanent increase in the investment rate, far from raising growth rates forever, affects growth for at most eight to ten years. With respect to the R&D-based models, the evidence against the models is even more compelling. These models predict that growth rates should be proportional to the level of R&D, which is clearly falsified by the tremendous rise in R&D over the last 40 years.

Jones [1995] suggests that this rejection of scale effects is potentially very serious. In an extension of Romer [1990] that maintains the micro foundations of the R&D-based models, the process of eliminating scale effects appears to eliminate the hallmark of the endogenous growth literature. In the extended model, the long-run growth rate is invariant to conventional government policies. However, recall the evidence in Figure I: nothing in the U. S. experience during the last century appears to have had a permanent effect on growth. In light of this evidence, the invariance results may be exactly what the data require.

APPENDIX A: CONTROLLING FOR ENDOGENEITY IN THE INVESTMENT REGRESSIONS

Because of the inclusion of the contemporaneous investment term in equation (7), the dynamic responses, calculated using OLS

will be biased, and the direction of the bias is typically ambiguous. Classical econometrics requires an instrument for current investment in order to obtain consistent estimates, 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 dynamic responses. The maximum 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 bounds.

To construct bounds on the dynamic responses, we use economic theory and the OLS estimates of equation (7) to calculate lower and upper bounds for the coefficient on the endogenous variable. Then, N^* specifications 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 estimate the remaining coefficients using OLS and calculate the dynamic responses. With a sufficiently fine grid (i.e., for N^* sufficiently large) the extreme values of these dynamic responses will bound the true values. Tests can be conducted using these extreme bounds.

First, we obtain an upper bound on c_0, the coefficient on the change in the contemporaneous investment rate. The OLS estimate of c_0 will be biased upward under the plausible assumption that the covariance between the innovation ϵ and current investment is positive, and therefore represents an upper bound on the true value.[24] This would be the case for most reasonable interpretations of the shocks that affect growth and investment. For instance, an 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.

To obtain the lower bound for c_0, recall that in simple growth models such as the Solow model or the AK models discussed earlier, the contemporaneous effect of a change in investment on

---

24. A simple "partialling out" argument can be used to show this, assuming that the covariance between ϵ and the lagged variables is zero.

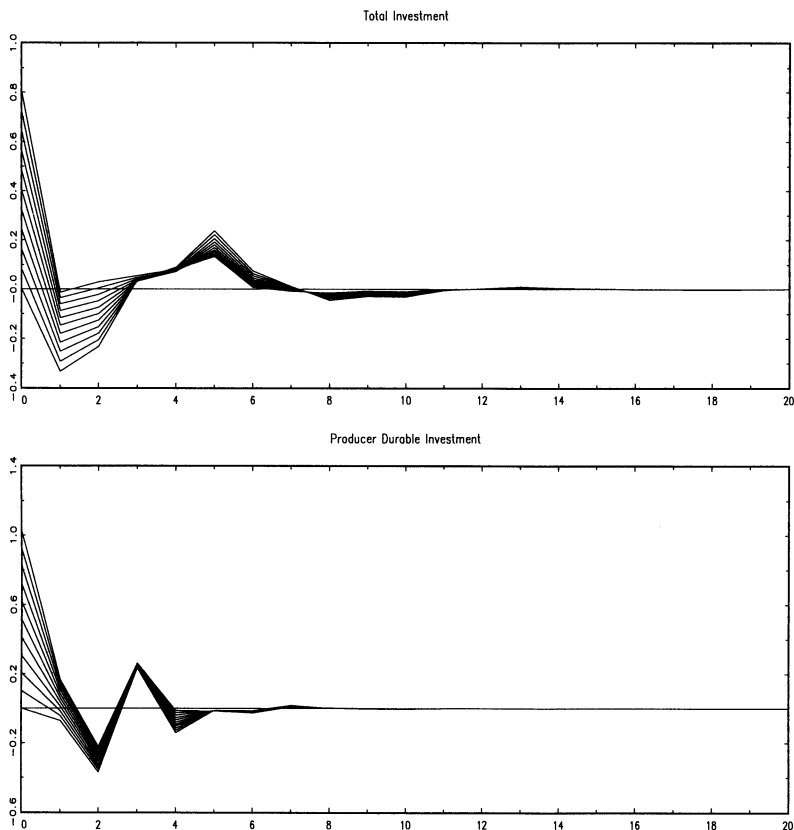Total Investment

Producer Durable Investment

FIGURE VI
OLS Bounds: Dynamic Response of Growth Rates to a Permanent One
Percentage Point Increase in the Investment Rate
Source. Author's calculations.

growth is nonnegative—a lower bound of zero then seems plausible.[25] 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.

Figure VI plots the dynamic responses for each of the $N^* = 11$ values of the contemporaneous response. The bounds for the short

25. An 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.

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. The result that permanent changes in investment have transitory effects on growth is robust to controlling for the endogeneity of the investment rate.

APPENDIX B: DATA APPENDIX

GDP per Capita and GDP per Worker. The data on GDP per capita for the period 1900–1987 (1880–1987 for the United States) are constructed from Maddison [1982, 1989] by Bernard [1991]. Data on GDP per worker for the period 1950–1988 are from Summers and Heston [1991].

Investment Rates. Total gross investment rates are taken from Summers and Heston [1991]. Data on producer durables investment rates were provided by Robert Summers.

Scientists and Engineers Engaged in R&D. Data for France, Germany, Japan, and the United States are taken from the NSF's *Science and Engineering Indicators 1989*. The U. S. data prior to 1965 are 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.

Total Factor Productivity Growth. Aggregate TFP growth data are from the OECD Department of Economic and Statistics Analytic Database and were provided by Steven Englander.

DEPARTMENT OF ECONOMICS, STANFORD UNIVERSITY

REFERENCES

Aghion, Philippe, and Peter Howitt, "A Model of Growth through Creative Destruction," *Econometrica,* LX (1992), 323–51.
Arrow, K. J., "The Economic Implications of Learning by Doing," *Review of Economic Studies,* XXIX (1962), 155–73.
Auerbach, A. J., K. A. Hassett, and S. D. Oliner, "Reassessing the Social Returns to Equipment Investment," Federal Reserve Board of Governors, R&S Working Paper #129, 1992.
Bai, J., R. Lumsdaine, and J. Stock, "Testing for and Dating Breaks in Integrated and Cointegrated Times Series," Working Paper, 1991.
Barro, Robert, "Economic Growth in a Cross Section of Countries," *Quarterly Journal of Economics,* CVI (1991a), 407–43.

——, "Government Spending in a Simple Model of Endogenous Growth," *Journal of Political Economy*, XCVIII (1991b), S103–S125.

Ben-David, Dan, "Equalizing Exchange: Trade Liberalization and Income Convergence," *Quarterly Journal of Economics*, CVIII (1993), 653–80.

Benhabib, Jess, and Boyan Jovanovic, "Externalities and Growth Accounting," *American Economic Review*, LXXXI (1991), 82–113.

Bernard, Andrew, "Empirical Implications of the Convergence Hypothesis," Working Paper, Stanford University, 1991.

Bosworth, B., "Taxes and the Investment Recovery," *Brookings Papers on Economic Activity*, (1985), 1–38.

De Long, J., Bradford, and Lawrence H. Summers, "Equipment Investment and Economic Growth," *Quarterly Journal of Economics*, CVI (1991), 445–502.

Dickey, David A., and W. A. Fuller, "Distribution of the Estimators for Autoregressive Time Series with a Unit Root," *Journal of the American Statistical Association*, LXXIV (1979), 427–31.

Easterly, William, "Distortions and Growth in Developing Countries," Working Paper, World Bank, 1991.

Economic Report of the President, 1990 (Washington, DC: Government Printing Office, 1990).

Fuller, W. A., *Introduction to Statistical Time Series* (New York: John Wiley, 1976).

Grossman, G., and E. Helpman, *Innovation and Growth in the Global Economy* (Cambridge: MIT Press, 1991a).

Grossman, G., and E. Helpman, "Quality Ladders in the Theory of Growth," *Review of Economic Studies*, LVIII (1991b), 43–61.

Jones, Charles I., "Economic Growth and the Relative Price of Capital," *Journal of Monetary Economics*, XXXIV (1994), 359–82.

——, "R&D-Based Models of Economic Growth," *Journal of Political Economy* (1995), forthcoming.

Kremer, Michael, "Population Growth and Technological Change: One Million B.C. to 1990," *Quarterly Journal of Economics*, CVIII (1993), 681–716.

Lucas, Robert E., Jr., "On the Mechanics of Economic Development," *Journal of Monetary Economics*, XXII (1988), 3–42.

Maddison, Angus, *Phases of Capitalist Development* (Oxford, UK: Oxford University Press, 1982).

——, *The World Economy in the 20th Century* (Paris: Development Centre of the OECD, 1989).

Mankiw, N. Gregory, David Romer, and David N. Weil, "A Contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics*, CVII (1992), 407–38.

Newey, W. K., and K. D. West, "A Simple Positive Semi-Definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix," *Econometrica*, LV (1987), 703–08.

Rebelo, Sergio, "Long-Run Policy Analysis and Long-Run Growth," University of Rochester, manuscript, 1987.

Rivera-Batiz, L., and P. Romer, "Economic Integration and Endogenous Growth," *Quarterly Journal of Economics* CVI (1991), 531–55.

Rivera-Batiz, L., and P. Romer, "Long-Run Policy Analysis and Long-Run Growth," *Journal of Political Economy*, XCIX (1991), 500–21.

Romer, Paul M., "Increasing Returns and Long-Run Growth," *Journal of Political Economy*, XCIV (1986), 1002–37.

——, "Crazy Explanations for the Productivity Slowdown," *NBER Macroeconomics Annual* (Cambridge: MIT Press, 1987).

——, "Endogenous Technological Change," *Journal of Political Economy*, XCVIII (1990), S71–S103.

Scott, M. F. G., "Policy Implications of a New View of Economic Growth," *Economic Journal*, CII (1992), 622–32.

Summers, Robert, and Alan Heston, "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950–1988," *Quarterly Journal of Economics*, CVI (1991), 327–68.

U. S Department of Education, *Digest of Education Statistics* (Washington, DC: Government Printing Office, 1988).