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**Investment Rate and Economic Growth in the Long Run:
Empirical Tests of Endogenous Growth Models**

by

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A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

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Abstract

Most endogenous growth models, particularly the *AK* model and the Lucas (1988) model, imply that the investment rate exerts a positive effect on the growth rate in the long-run. This hypothesis is tested in this study, using time-series and panel data for the Organization for Economic Co-operation and Development (OECD) countries.

The thesis is divided into two parts. First, Jones' (1995) time-series tests of the one-sector *AK* model are re-examined, using improved data sets and a new empirical procedure. The two data sets used in this study are the annual time-series data on the investment and growth rates for 24 OECD countries during 1950–1990, and for six major OECD countries during 1870–1987. The empirical procedure accounts for the correlation between independent variables and disturbance terms arising from cyclical shocks and transitional dynamics in economies. This procedure yields consistent estimates of long-run multipliers from the investment rate to the growth rate. This re-examination casts doubt on Jones' finding that the investment rate has no positive growth effect in the long run. Considerable evidence is found for a positive long-run effect of the investment rate on the rate of growth.

The tests are then extended to the two-sector endogenous growth model of Lucas (1988). The steady-state solution of the model implies a long-run linkage between the growth and investment rates, similar to that implied by the one-sector *AK* model. The transitional dynamics of the model suggest that the growth rate also depends on the ratio

of physical to human capital. Three variants of the Lucas two-sector model are examined and tested using pooled time-series data on 22 OECD countries during 1965–1987. The investment rate continues to have a positive long-run effect on the rate of growth. Also, the ratio of physical to human capital significantly raises the model's predictive power and is therefore indispensable to growth regression. These results are robust to alternative measures of human capital and to adjustments in the ratio of capitals for the externalities of human capital.

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CHAPTER 1

INTRODUCTION

The linkage between investment and growth has been at the core of economic growth theory at least since Harrod (1939) and Domar (1946). Solow (1956) formalized the idea that capital deepening can increase labour productivity in a dynamic process of investment and growth. In a whole class of neoclassical growth models inspired by Solow (1956) — including those of Cass (1965) and Koopmans (1965) — the steady-state rate of growth of per capita income depends only on the rate of technological progress, which in turn depends on forces exogenous to the growth models. Therefore, neoclassical growth models predict that the rate of investment, along with a number of other variables potentially affected by government policies, has no effect on the rate of growth in the steady state of an economy, although it can affect the steady-state level of per capita income; i.e., neoclassical growth models imply that these variables have a *level effect* but no *growth effect*.¹

¹ Solow (1956) considered a case in which the population growth rate depended endogenously on the level of per capita income. In that case, a change in the investment rate may affect the rate of long-run growth. But most neoclassical growth models after Solow (1956) treated the population growth rate as an exogenous parameter.

Endogenous growth models, such as those in the recent pioneering work of Romer (1986) and Lucas (1988), differ from neoclassical growth models in that the long-run rate of growth is determined by forces within the models, not by those operating from outside. Nearly a decade of active research on the determinants of long-run growth has generated a rich variety of endogenous growth models.² Most of these models imply that the rate of investment in physical capital, human capital or knowledge has a positive effect on the long-run growth. The essence of endogenous growth can be seen most easily by looking at the simple one-sector model with constant returns to broadly defined capital. Growth model of this type, often referred to as the *AK* model, include those of Romer (1986, 1987), Barro (1990) and Rebelo (1991). In contrast to neoclassical growth models, an *AK* model implies that the rate of investment in broadly defined capital — including not only physical but also human and knowledge capital — has a *growth* effect, i.e., a higher rate of investment leads to a higher rate of growth in the steady state. Because the *AK* model differs from neoclassical growth models in implying that the investment rate has a positive effect on the growth rate, a test of this model can take the form of a test of the long-run growth effect of the investment rate. A positive long-run effect of the investment rate on the growth rate would support the *AK* model; an absence of this effect would favour neoclassical growth models.

Three approaches have been taken in empirical tests of endogenous growth

² For a few examples of the extensive literature on endogenous growth models, see Romer (1990), Grossman and Helpman (1991), Rebelo (1991), Rivera-Batiz and Romer (1991) and Aghion and Howitt (1992). Grossman and Helpman (1994), Barro and Sala-i-Martin (1995), Romer (1996), McCallum (1996), Jones and Manuelli (1997) and Temple (1998) provide good surveys of endogenous growth literature.

models: cross-country (or cross-sectional) regression, time-series analysis and case studies. The cross-country regression is by far the most popular approach. A number of cross-country regressions have shown a positive correlation between the investment rate (measured as the share of physical-capital investment in gross domestic product [GDP] and serving as a proxy for the rate of saving) and the rate of growth of per capita GDP (see, for example, Romer 1987; Barro 1991; Levine and Renelt 1992; Dinopoulos and Thompson 1997a). The specifications of these tests and the details of the results vary considerably from one study to another, but the essence of the cross-sectional evidence can be illustrated by a simple correlation between growth and investment rates. Figure 1.1 plots the average growth rate of per capita GDP versus the average investment rate during 1960–1987 for 85 countries. The figure clearly shows a positive relationship between the investment rate and the rate of growth.

However, it has to be noted that the cross-country-regression approach to the test of endogenous growth models has its limitations. The approach is based on data averaged over a long period. The test therefore fails to capture the transitional-dynamic behaviour of the variables. If the economies in the sample are in transition, rather than a steady state, the estimates from a cross-country regression would be biased.³ This is because in many endogenous growth models, as in neoclassical models, deviations of growth rates from their steady states arise directly from changes in regressors; hence, the deviations are not

³ In their recent cross-country test of the research and development (R&D)-based long-run growth model of Romer (1990), Dinopoulos and Thompson (1997a) suggested that this potential bias could be one of the reasons why the Romer model failed to account for the wide variation in growth rates in their sample.

**Figure 1.1 The correlation between growth and investment rates:
a simple cross-country regression**

Source: Nehru et al. (1995)

random or independent of the regressors. For this reason, cross-country regressions do not settle the issue of whether the investment rate is a determinant of long-run growth. For example, while the advocates of endogenous growth theory, such as Romer (1987) and Rebelo (1991), hold that the positive correlation between growth and investment rates found in cross-country regressions is consistent with the predications of endogenous growth models, those who support neoclassical growth theory (notably, Mankiw 1995) maintain that this correlation may merely reflect the transitional effect of the investment rate on the growth rate and thus accords with the predictions of neoclassical growth

models.

Because of these problems with cross-country regression,⁴ interest is growing in time-series and panel-data tests of growth models.⁵ Many researchers have recognized that the relevance and usefulness of endogenous growth theory ultimately depends on whether it successfully explains the growth patterns of national economies. In practice, this means testing the implications of the theory against the economic evolution of individual countries, using time-series data.⁶

In an interesting recent time-series test of endogenous growth models, Jones (1995) found that many *AK*-style (as well R&D-based) models of endogenous growth are rejected by the time-series evidence from selected OECD countries. The key results from his test of the *AK* model are as follows: (1) During 1950–1988, investment rates for many of the advanced OECD countries exhibited an upward trend, but the growth rates showed little or no persistent increase; indeed, the growth rates went down in many of these countries. (2) Individual-country time-series regressions showed that the investment rate had no positive long-run effect on the growth rate. (3) The transitional effect of the investment rate on the growth rate was short lived; the effect became negligible after

⁴ See Mankiw (1995) and Temple (1998) for other problems and difficulties with cross-country studies, i.e., problems of parameter heterogeneity, simultaneity, multicollinearity, outliers and degrees of freedom.

⁵ Among the relatively small but growing number of empirical works on time-series tests of various growth models are those of Coe and Helpman (1995), Jones (1995) and Brecher et al. (1996).

⁶ Pack (1994) made this point in his review of recent empirical tests of endogenous growth models.

about six years. On the basis of these results, Jones (1995, p. 510) concluded that “the predictions of *AK* models are not only technically incorrect but they are also misleading.”

This study follows the tradition of Jones (1995) by undertaking further time-series tests of the *AK* model. I re-examine Jones’ tests using improved data sets and a more appropriate empirical procedure. The data used in this study differ in two ways from those used in Jones’. First, I use the recently updated Summers and Heston’s (1991) Penn World Table (Mark 5.6) data set (PWT5.6, hereafter), instead of Penn World Table (Mark 5) (PWT5, hereafter), as the main data source for OECD countries in the post-war era. Second, I use, in addition to the Maddison (1982, 1989) data on long-run growth rates used by Jones, the Maddison (1991a) data on long-run investment rates for six major developed countries. The empirical procedure used in this study takes into account the correlation between investment rates and disturbance terms arising from cyclical shocks in an economy. With this empirical procedure, consistent estimators are generated for the long-run effect of investment rates on growth rates. This finding raises doubts about some of Jones’ (1995) results by showing that the time-series evidence from OECD countries, in fact, accords with the implications of the *AK* model.

Although the time-series evidence is broadly supportive of the one-sector *AK* model, some researchers remain sceptical about the model.⁷ This is partly due to the model’s simple one-sector linear production function and its lack of transitional dynamics.

⁷ For example, before Jones (1995) conducted his time-series tests, Young (1992) criticized and rejected the *AK* model, using case-study evidence from Hong Kong and Singapore. But the evidence he used to reject the *AK* model is debatable, according to some other leading economists, including Barro (1992).

For this reason, this study derives the endogenous growth hypothesis from a class of models that are variants of the Lucas (1988) model. These models have the basic feature of the *AK* model in exhibiting constant returns to accumulated factors, but depart from it in two critical ways. First, they have two sectors of production: one sector produces human capital or knowledge, while the other produces goods and service, including physical capital. Second, they have well-behaved transitional dynamics. Therefore, these models can be thought of as two-sector extensions of the *AK* model.⁸ The steady-state solutions of these models imply a long-run relationship between the growth and investment rates similar to that implied by the one-sector *AK* model; i.e., the long-run growth rate depends positively on the investment rate. A unique implication of the model's transitional dynamics is that during the transition period, the growth rate depends not only on the investment rate but also on the ratio of physical to human capital. This study tests these two-sector endogenous-growth hypotheses, using pooled-time-series data on 22 OECD countries, and the results of this study provide considerable support for these two-sector endogenous growth models.

The rest of this study is organized as follows. In Chapter 2, I present a brief review of the *AK* model and the existing time-series evidence for the model. This review emphasizes the empirical regularities — time trends and long-run co-movements — of the

⁸ While some authors — including Jones (1995) and Dinopoulos and Thompson (1997a) — equate the Lucas (1988) model and its variants with the *AK* model, others — including Barro and Sala-i-Martin (1995), McCallum (1996) and Jones and Manuelli (1997) — treat them as a separate class. I call the Lucas model and its variants *the two-sector extensions of the AK model* to emphasize these models' two-sector structure and their transitional dynamics.

investment and growth rates in the two data sets for OECD countries. Contrary to the findings of previous studies, the empirical regularities of the growth and investment rates emerging from these data sets, especially from the data on the growth and investment rates for more than a century, are broadly consistent with the predictions of the *AK* model.

In Chapter 3, I draw on recent techniques in time-series analysis to develop an empirical procedure for formal tests of the *AK* model. To deal with the correlation between the error terms of the growth regression and the regressor (i.e., the investment rate) arising from cyclical shocks in an economy, the procedure augments the regression with leads and lags of the first-difference terms of the investment rate. Regressions for the 24 OECD countries during 1950–1990 show considerable support for the *AK* model, as the investment rate is found to have a significantly positive long-run effect on the growth rate in half of these 24 countries. Further and stronger evidence for the *AK* model is found in regressions using an annual time series for six major OECD countries during 1870–1987 and in the pooled time-series regressions for 24 OECD countries during 1950–1990. Estimates of the effects based on both Ordinary Least Square (OLS) and Seemingly Unrelated Regression (SUR) estimators are significantly positive in all four cases examined, which range from the basic pooled-time-series specification to the variable-intercept and variable-slope-coefficient specifications.

Chapter 4 derives the endogenous growth hypothesis from the variants of Lucas (1988) two-sector endogenous growth models with transitional dynamics, including the basic Lucas model, the Lucas externality model, and the generalized Lucas two-sector model. I show that the linear long-run relationship between growth and investment rates

found in the one-sector *AK* model also hold in the basic Lucas model and in the Lucas externality model. The ratio of physical to human capital has no effect on the growth rate in the steady state of these two variants but plays an important role in the growth regression because it affects the growth rate during the transition period. The positive linkage between investment and growth rates continues to exist in the generalized Lucas two-sector endogenous growth model. But the generalized model also suggests the long-run linkage between the ratio of physical to human capital and the rate of growth may be negative.

In Chapter 5, I test the endogenous growth hypothesis derived from three variants of the Lucas (1988) model, using pooled time-series data on investment and growth rates for 22 OECD countries. The regression results from a variety of specifications of the models, using two different measures of human capital, show that the investment rate has a significantly positive long-run effect on the long-run growth. The long-run effect of the ratio of physical to human capital is generally negative and significant. Although it is unclear whether the negative long-run effect of this ratio arises because of a long transition period in the OECD economies or the externalities of human capital, it is obvious that the ratio improves significantly the predictive power of the model. Therefore, the ratio of capitals is an indispensable component of growth regression.

In Chapter 6, I provide some conclusions, summarize the findings, discuss the implications of the test results and identify avenues of future research.

CHAPTER 2

THE TIME-SERIES EVIDENCE FOR THE ONE-SECTOR *AK* MODEL

The simple structure and the straightforward implication of the *AK* model make it an ideal starting point in the test of endogenous growth theory. This chapter briefly lays out the *AK* model of endogenous growth, explains the basic test of the model, and reviews the existing time-series evidence for the model, based on the long-run trends of investment and growth rates. The chapter also sets the stage for the formal empirical test that I develop and implement in the following chapters.

2.1. The *AK* Model of Endogenous Growth

A one-sector *AK* model, with two types of capital, can be simply expressed as

$$\text{Max} \int_0^{\infty} \exp(-\rho t) \frac{c_t^{1-\theta} - 1}{1-\theta} dt, \quad (2.1)$$

subject to

$$y_t = Bk_t^{\alpha}h_t^{1-\alpha}, \quad (2.2)$$

$$c_t = (1 - i_t^k - i_t^h) y_t, \quad (2.3)$$

$$\dot{k}_t = i_t^k y_t - (\delta^k + n) k_t, \quad (2.4)$$

$$\dot{h}_t = i_t^h y_t - (\delta^h + n) h_t, \quad (2.5)$$

where ρ is the rate of time preference; θ is the inverse of the elasticity of intertemporal substitution between consumption at times t_1 and t_2 ($-\theta$ is the elasticity of marginal utility); c_t is the per capita consumption; k_t and h_t are per capita physical and human capital, respectively; α is the share of physical capital; y_t is per capita output, which can be used on a one-for-one basis for consumption, investment in physical capital, or investment in human capital; i^k and i^h are the investment rates in physical and human capitals (i.e., the fractions of output y_t allocated to physical- and human-capital investment, respectively); δ^k and δ^h are the depreciation rates of physical and human capital; n is the population growth rate; and B is a positive constant representing the level of technology.

The defining feature of this model is that the production function — i.e., equation (2.2) — exhibits constant returns to the physical and human capitals. This feature of the production function plays a key role in generating the long-run growth. It can be shown that if the ratio of physical to human capital is defined as ω_t , i.e., $\omega_t = k_t/h_t$, then in equilibrium, this ratio is constant and equal to the relative income share of the two capitals, i.e., $\omega^* = \alpha/(1-\alpha)$.⁹ Using this result, equation (2.2) can be re-written as

⁹ See Barro and Sala-i-Martin (1995, chapter 4).

$$y_t = A k_t, \quad A \equiv B \left(\frac{\alpha}{1-\alpha} \right)^{-(1-\alpha)}. \quad (2.6)$$

Thus, with two types of capital, this model behaves exactly the same as the one in that output is a linear function of one capital good (hence the name, “ AK model”). One can view K as a proxy for a composite of capital goods including physical and human components.

The steady state of the AK model features constant and equal rates of growth for y , k , and c .¹⁰ Using equations (2.6) and (2.4), the steady-state rate of growth can be expressed as

$$g^* = -(\delta^k + n) + A i^*, \quad (2.7)$$

where g^* is the common growth rate of output, consumption, physical capital and human capitals, and i^* is the steady-state rate of physical-capital investment.

Equation (2.7) indicates that the rate of growth is a linear function of the rate of investment. According to equations (2.6) and (2.7), the responsiveness of the growth rate to a change in the investment rate depends on the average product of physical capital, A , which in turn depends positively on the level of technology and negatively on the ratio of

¹⁰ Some authors use the term *balanced growth* for the paths in which all variables grow at constant and equal rates. I use the terms *steady state* and *balanced growth* interchangeably.

physical to human capital.

The significance of equation (2.7) is that it provides a testable hypothesis regarding the steady-state relation between the rates of growth and investment. This relation implies that a higher steady-state rate of investment is associated with a higher steady-state rate of growth. If two economies differ in investment rates but have the same rates of depreciation and population growth, the same ratio of physical to human capital, and the same levels of technology, then in the steady state the one with the higher investment rate grows faster. In other words, a public policy that raises the rate of investment in the long-run could lead to a higher rate of growth in the long-run.

This implication of the AK model stands in marked contrast to that of neoclassical growth models. In the latter, the growth rate of per capita income in the steady state is pegged at an exogenous rate of technological progress. A higher rate of investment results in a higher rate of growth only in the transition period but not in the long-run. This result is due to the active role of diminishing returns to capital accumulation in neoclassical models. Capital accumulation may increase the growth rate in the transition period, but the diminishing returns to capital will eventually bring the rate of capital accumulation down to the exogenously determined steady-state growth rate.¹¹ On the

¹¹ Consider a familiar neoclassical production function:

$$y_t = A k_t^\alpha, \quad (\text{A2.1})$$

where A is the level of technology. The usual equation of capital accumulation is given by

$$\dot{k}_t = i_t y_t - (\delta + n) k_t, \quad (\text{A2.2})$$

The rate of capital accumulation is given by

other hand, because the mechanism of diminishing returns to capital has no role in the AK model, it poses no limit on the capital accumulation and therefore none on long-run growth.

2.2. The Post-War Time-Series Evidence for the AK Model

According to the AK model, the long-run rate of growth depends on the investment rate. Therefore, an inspection of trends in growth and investment rates in developed countries can serve as a starting point in the empirical test of long-run growth. Jones (1995) applied this method very effectively in his recent time-series test of the AK model. The most intuitively powerful piece of evidence he used against the AK model is that though the investment rates went up in many OECD countries during 1950–1988, the growth rates in most of these countries actually went down, contrary to the AK model's prediction. This result, reproduced from Jones' (1995; tables II and IV, on pp. 500 and 507), is reported in columns 2 and 3 in the following Table 2.1. Column 2 shows that the investment rate has a significantly positive trend in five of the 15 selected OECD countries, but column 3 shows that the growth rate has no significantly positive trend in

$$g_k = \frac{A}{k_t^{1-\alpha}} i_t - (\delta + n). \quad (\text{A2.3})$$

Equation (A2.3) appears similar to equation (2.7), but with a crucial difference. Equation (2.7) can generate a positive growth rate even if A is constant; but equation (A2.3) cannot support a positive growth rate unless A grows at an exogenously determined rate: if A is constant but the capital stock grows, then $A/k_t^{1-\alpha}$ will eventually approach to zero. Therefore, the steady-state rate of growth in a neoclassical growth model depends on the rate of technological progress, rather than on the rate of investment.

any of these 15 countries.

However, two data problems plagued Jones' study. First, Jones' results were based on data from PWT5. Since his study this data set has been substantially revised and extended. These revisions and extensions include the following: some series, e.g., the investment rate in the United States, were revised in PWT5.6 because of data errors in the early version;¹² most series were updated and extended from 1988 to 1992; new methodologies were used in PWT5.6, resulting in improvements in data quality.¹³ Second, Jones used the real GDP per worker in constant international prices (i.e., *RGDPW* series) to calculate the growth rate, but to represent the investment rate he chose the series of gross domestic investment as a percentage of GDP in current international prices (i.e., the *CI* series), rather than gross domestic investment as percentage of GDP in constant international prices (i.e., the *I* series). This is apparently inappropriate because, on the one hand, the two series have different price bases, and they are therefore incomparable; on the other, as indicated by Summers and Heston (1991), series based on current prices are generally not intertemporally comparable.¹⁴

¹² See Figure A2.1 in Appendix II for an illustration of the difference in the investment rate between the two versions.

¹³ See *About PWT5.6* on the University of Toronto's website: <http://www.epas.utoronto.ca:5680/pwt/pwt.html>.

¹⁴ A time series of investment rate based on constant prices and that based on current prices will be identical if and only if the price indices of investment goods and those of the other components of GDP are identical. This is, however, rarely the case.

Table 2.1 Time trends of investment and growth rates in 15 selected OECD countries. ^a

Country	Jones' results (1950–1988) ^b		Results based on PWT 5.6 (1951–1990)			
	Investment rate ^c	Growth rate ^{c,d}	Investment rate ^c		Growth rate ^{c,d}	
			Trend	R ²	Trend	R ²
Australia	-0.083 (-1.50)	-0.010 (-0.15)	-0.057 (-1.36)	0.068	-0.028 (-0.78)	0.009
Austria	0.279*** (4.46)	-0.110** (-2.53)	0.150** (2.33)	0.298	-0.145*** (-4.16)	0.315
Belgium	0.034 (0.41)	-0.032 (-0.68)	-0.041 (-0.57)	0.028	-0.048 (-1.43)	0.058
Canada	0.083*** (1.91)	0.020 (0.38)	0.047 (1.31)	0.097	-0.021 (-0.66)	0.008
Denmark	-0.018 (-0.11)	-0.029 (-0.41)	0.027 (0.025)	0.006	-0.062 (-1.52)	0.056
Finland	-0.068 (-0.69)	-0.036 (-0.63)	-0.080 (-1.25)	0.081	-0.081** (-2.78)	0.071
France	0.166 (1.68)	-0.087** (-2.38)	0.119 (1.41)	0.163	-0.106*** (-4.00)	0.349
Germany	-0.146** (-2.12)	-0.153*** (-3.26)	-0.165*** (-2.80)	0.418	-0.172*** (-6.44)	0.411
Italy	-0.095 (-0.85)	-0.095** (-2.63)	-0.193** (-2.33)	0.376	-0.130*** (-5.24)	0.285
Japan	0.426*** (2.84)	-0.182*** (-3.07)	0.432*** (3.70)	0.547	-0.134*** (-3.35)	0.244

Table 2.1 (Continued)

Country	Jones' results (1950–1988)		Results based on PWT 5.6 (1951–1990)			
	Investment rate	Growth rate	Investment rate		Growth rate	
			Trend	R ²	Trend	R ²
Netherlands	-0.140 (-1.36)	-0.075 (-1.40)	-0.089 (-1.22)	0.101	-0.104** (-2.66)	0.149
Norway	-0.036 (-0.64)	0.025 (0.73)	-0.128** (-2.06)	0.181	-0.067*** (-3.00)	0.190
Sweden	-0.033 (-0.43)	-0.033 (-1.00)	-0.036 (-0.57)	0.026	-0.059** (-2.76)	0.156
United Kingdom	0.158** (2.71)	0.002 (0.06)	0.095** (2.02)	0.235	-0.010 (-0.38)	0.003
United States	0.068** (2.18)	0.001 (0.01)	-0.019 (-1.61)	0.034	-0.029 (-1.09)	0.017

Note: ^a This table reports the estimate of b from the equation $y_t = a + bT + e_t$, where y_t is the growth rate or investment rate; and T is a time-dummy variable.

^b Reproduced from Jones' (1995; tables II and IV, on pp. 500 and 507).

^c The Newey and West (1987) t -statistics (robust-White and robust to autocorrelation) are reported in parenthesis. ** *** indicate significant at 5% and 1% levels, respectively.

^d The growth rates are multiplied by 100 in this table.

The results of a time-trend regression using the growth and investment rates from PWT5.6 are reported in columns 4 to 7 in Table 2.1.¹⁵ These results clearly differ from those of Jones (1995), particularly in time trends in investment rates. Column 4 shows that during 1951–1990, the investment rate had a significantly positive trend in only three of these 15 countries, and it had a significantly negative trend in three others. According to these new results, the investment and growth rates move in the same direction (i.e., time trends have a common sign) in a majority (nine in 15) of the OECD countries in the sample. Only in two of these 15 countries, i.e., Austria and Japan, were the trends in the investment rate significantly positive while the trends in the growth rate were significantly negative. But, as I show later in this chapter, the post-war time trends in Japan fails to capture the steep up-swings in the investment and growth rates before 1973 and the sharp down-swings after 1973. If one extends the sample period back to the last century, then one can see clearly that both growth and investment rates in Japan have increased significantly. On the whole, therefore, the time-trend analysis gives support, albeit weak, to endogenous growth theory.

Although the evidence concerning the time trends in the growth and investment rates for OECD countries in the post-war era is straightforward and informative, these results are limited in two ways. First, a comparison of the simple deterministic time trends of growth and investment rates may be inadequate to reflect the complex long-run dynamic relationship between the two variables. For instance, deterministic time trends

¹⁵ See Table A2.1 in Appendix II for differences between Jones' (1995) data sets and those used in this study.

fail to capture up- and down-swings or structural breaks in economic growth.¹⁶ Second, the time trends estimated for a short time span may fail to provide any good indication of long-run behaviour. Endogenous growth theories imply a long-run linkage between growth and investment rates, but this linkage does not necessarily emerge from observations made over only four decades. One indication of the inadequacy of the simple deterministic time-trend regressions is the low values of R^2 . As one can see from Table 2.1, in most of these 15 OECD countries, the time trends only explain a very small portion (often less than 10%) of the variations in growth and investment rates.

2.3. The Long-Run Perspective

To better understand the long-run dynamic relation between investment and growth rates, I examine the annual time series in five major developed countries during 1870–1987. These five countries — Australia, Canada, Japan, the United Kingdom, and the United States — were selected purely on the basis of availability of continuous annual data on investment and growth rates from 1870 to 1987, using Maddison's (1982, 1989, 1991a) data set. The long-run stochastic trends were extracted from the series of growth and investment rates using the filter of Hodrick and Prescott (1980).¹⁷ To facilitate

¹⁶ Interestingly, a number of prominent economists — first N.D. Kondratieff, then S. Kuznets and J. A. Schumpeter — believed that there were long waves in long-run economic growth, which also cannot be explained by deterministic trends. See Maddison (1991b, chapter 4) for a review of the long-wave theory.

¹⁷ Hodrick–Prescott (HP) filter is a two-sided symmetric moving-average filter. It decomposes a time series into a cyclical component and a trend (or growth) component.

comparison between the two series, the trends were then normalized for each series, giving each a mean of zero and a standard deviation of 1.¹⁸ The results are presented in Figure 2.1.

Figure 2.1 shows that during 1870–1988, growth rates moved with investment rates fairly closely in most of these five countries. In general, the trend components of the growth rates fluctuated more widely than those of the investment rates, especially during 1914–1945 (indicated by the grey areas in the graphs), which includes the two world wars and the Great Depression. However, the trend components of the two series seem to be linked. The long-run dynamic linkage between the growth and investment rates has two characteristics. One is a common upward drift in the two series. The other is that the up- and down-swings in one series are generally followed by similar swings in the other. The common drift is particularly obvious in Australia, Japan and the United Kingdom, where both series have clear positive long-run trends, but the similarity of up- or down-swings between the two series can be seen in all five countries at various times.

Singleton (1988) showed that the HP filter operates like a high-pass filter when applied to stationary time series. A high-pass filter removes the low-frequency or long-cycle components and allows the high-frequency or short-cycle components to pass through (see Cogley and Nason 1995).

¹⁸ Another widely used alternative way of showing the trends of time series is to plot the moving average of the series. As I show in Figure A3.1, in the Appendix III, a similar long-run relation between the growth and investment rates is evident in the five-year-moving-average graphs for these countries.

Figure 2.1 A long-run perspective on the investment and growth rates in five major developed countries, 1870–1987

Note: The Hodrick–Prescott trend components of the growth rate are plotted as solid lines, and those of the investment rate are shown as dotted lines. The grey areas cover the two world wars and the years between the wars. Both series are normalized so that each of them has a mean of zero and a standard deviation of 1.

Source: See Appendix II.

The graphs in Figure 2.1 provide a long-run historical perspective and help us to better understand the relationship between investment and growth rates in certain periods. For example, during the post-war period, almost all of the five countries initially experienced strong up-swings in both investment and growth rates, followed by dramatic down-swings in the growth rate and, to a lesser extent, the investment rate. But this is only an episode in the long-run dynamics of the two series. The deterministic time trends derived from this period alone (as shown in Table 2.1) not only fail to capture the up- and down-swings in each series, they may even be misleading. The case of Japan is the most typical. The observations on the growth and investment rates in Japan during 1950–1990 give a positive time trend for the investment rate and a negative time trend for the growth rate. But broadening the horizon and comparing the behaviour of the two series since 1885, one can see a clear upward drift in the rates of both growth and investment. For another example, the decline in growth rates, and to a lesser extent in investment rates, occurring in many developed countries after mid-1970 was not necessarily a sign of permanent productivity slowdown. Indeed, the graphs show that the growth rates started to rebound in the early 1980s in four of the five countries, excluding Japan.

2.4. Summary

This chapter briefly lays out the one-sector AK model and presents some informal but intuitive time-series evidence for the model. Two main findings emerge from the empirical regularities contained in the two data sets: one for 15 OECD countries in the

post-war era and the other for five major OECD countries since 1870. First, the time trends in growth and investment rates move in the same direction in a majority of the 15 selected OECD countries during 1950–1990. Second, although the two series fluctuate widely in the five major OECD countries since 1870, they seem to drift upward together, and they track each other quite closely in the sense that the up- and down-swings in one series are often followed by similar swings in the other. Both findings are consistent with the prediction of the *AK* model.

CHAPTER 3

TIME-SERIES TESTS OF THE ONE-SECTOR *AK* MODEL RE-EXAMINED

The historical evidence in the preceding chapter is illuminating but informal; it fails to exploit fully the potential of time-series analysis. In this chapter, I draw on the recent techniques in time-series analysis to develop an empirical procedure to estimate the long-run relation between growth and investment rates; I then use this procedure to test the endogenous growth hypothesis implied by the one-sector *AK* model; i.e., that the investment rate has a positive long-run effect on the growth rate.

3.1. The Empirical Procedure for Estimating the One-Sector Model

The dynamic relation between growth and investment rates implied by the *AK* model (i.e., equation [2,7]) can be expressed as the following distributed lag model:

$$g_t = \alpha + B(L) x_t + e_t, \quad (3.1)$$

where g_t is the growth rate; α is a constant; $B(L)$ is a polynomial of order p in the lag operator L , e.g.,

$$B(L) = b_0 + b_1L + b_2L^2 + \dots + b_pL^p, \quad (3.2)$$

where $b_0, b_1, \dots, b_p$ are the lag coefficients; x_t denotes the investment rate at time t ; and ε_t is the disturbance term, which includes cyclical shocks in the economy. Both g_t and x_t are assumed to be stationary. It follows that ε_t is also stationary.

One major problem with estimating the long-run relation between growth and investment rates using equation (3.1) is that the independent variable x_t and its lagged values may be correlated with the disturbance term ε_t . Such correlation can arise because of cyclical fluctuations in the economy.¹⁹ These fluctuations (included in ε_t) tend to affect both growth and investment rates, causing them to deviate from their long-run values. The disturbance term ε_t would thus be correlated with current and lagged values of the investment rates.²⁰ It is well known that if the regressors are correlated with the disturbance terms, then the OLS estimators will be biased and inconsistent. In recent literature on empirical tests of growth models, many authors — including Barro and Sala-i-Martin (1995, chapter 12), Mankiw (1995) and Jones (1995) — have noted another potential source of bias in OLS estimators, i.e., the possible reverse causality from growth

¹⁹ In models with transitional dynamics, the transitional factors in the economy will also cause this correlation. I discuss this case in Chapter 5.

²⁰ The deviation of the measured growth rate of labour productivity from its long-run value could stem from, for instance, variations in capacity utilization and labour hoarding in response to the business cycle, whereas the deviation of the investment rate could be directly caused by cyclical fluctuations in output. See Brecher et al. (1996) for a similar argument in an endogenous sectoral-productivity growth model.

to investment rate.

One way to deal with the biases arising from cyclical disturbance or reverse causality would be to use instrumental variables.²¹ It is difficult, however, to find a satisfactory instrumental variable for investment rate. For instance, the lagged value of investment rate seems to be a natural choice as an instrumental variable for the current investment rate; however, since the error term in this model is, as in many other time-series models, likely to be serially correlated, this instrumental variable is of little help.

This study adopts an alternative procedure for dealing with these biases. The procedure was earlier used by Saikkonen (1991), Phillips and Loretan (1991) and Stock and Watson (1993) in the estimation of cointegration regressions.²² It is also well-suited to correct the correlation between the independent variables and the disturbance term in stationary regression models. For instance, it was recently applied by Brecher et al. (1996) in the estimation of sectoral-productivity growth models. The details of this procedure are described below.

First, isolate the long-run effect of the rate of investment on the rate of growth and rewrite equation (3.1) as

$$g_t = a + B(1) x_t + B'(L) \Delta x_t + e_t, \quad (3.3)$$

²¹ Some recent cross-countries studies used instrumental variables to avoid endogeneity problem, e.g., Barro and Sala-i-Martin (1995), Caselli et al. (1996) and Barro (1997).

²² See Hamilton (1994, pp. 608–613) for a detailed description of this procedure in the estimation of cointegrating regression.

where $B(1)$ is the sum of the coefficients in the polynomial $B(L)$, which captures the long-run effect of the investment rate on the growth rate, i.e.,

$$B(1) = b_0 + b_1 + b_2 + \dots + b_p; \quad (3.4)$$

$B'(L)$ is a lag polynomial, such that

$$b'_j = - \sum_{i=j+1}^p b_i, \quad j=0,1,\dots,p-1; \quad (3.5)$$

and Δx_t is the first difference of the investment rate x_t . Since the steady-state equation (2.7) represents the long-run relation between the growth and investment rates, it implies that $B(1) > 0$.

Next, consider a linear projection of the disturbance term ε_t on the current value of x_t and its leads and lags, i.e.,

$$\varepsilon_t = C(L) x_{t,q} + v_t, \quad (3.6)$$

where $C(L)$ is a lag polynomial of order $2 \times q$, which can be expressed as²³

$$C(L) = c_0 + c_1 L + c_2 L^2 + \dots + c_q L^q + c_{q+1} L^{q+1} + \dots + c_{2q} L^{2q}; \quad (3.7)$$

the parameter q represents the length of the lead and lag; and v_t is the residual. By construction, v_t is uncorrelated with x_t and its leads and lags. Because the short-run

²³ I assume that the correlation among x_t and ε_t is zero beyond q periods of lead or lag.

fluctuations in the economy affect both the growth and investment rates, the polynomial $C(L)$ contains non-zero coefficients. The rationale for relating ε_t to both the leads and lags of x_t is that the timing of the effects of the short-run shocks on investment and growth rates is unknown. These shocks can begin affecting the growth rate either before or after their initial impacts on the investment rate. Because cyclical shocks can only have a negligible effect on the growth and investment rates in the remote past or future, I assume that the correlation between x_t and ε_t is zero beyond q periods of lead or lag.

Cyclical shocks may cause the growth and investment rates to temporally deviate from long-run equilibrium, but they cannot alter the underlying parameters determining the equilibrium. In other words, no long-run relationship holds between the disturbance term and the investment rate. Thus, $C(1) = 0$.²⁴ Using this restriction, equation (3.6) can be rewritten as

$$\begin{aligned}\varepsilon_t &= C(1)x_t + C'(L)\Delta x_{t,q} + v_t \\ &= C'(L)\Delta x_{t,q} + v_t.\end{aligned}\tag{3.8}$$

Substituting in equation (3.3) for ε_t from equation (3.8) and rearranging it, one can arrive at the following:

$$g_t = a + B(1)x_t + D'(L)\Delta x_{t,p} + v_t,\tag{3.9}$$

²⁴ The restriction $C(1) = 0$ plays a critical role in deriving equation (3.9). This restriction is consistent with the standard view of long-run growth. However, in some macroeconomic models, the cyclical effect can permanently affect the path of the economy. See, for example, the model with hysteresis in Blanchard and Summers (1986).

where $D'(L) = C'(L)$ for $p > 0$ (i.e., for leads of Δx_t) and $D'(L) = B'(L) + C'(L)$ for $p \leq 0$ (i.e., for current and lagged terms of Δx_t). In general, difference may occur in the lag lengths of $B'(L)$ and $C'(L)$, which are p and q , respectively. This is because lag length p depends on how long it takes to capture the long-run effect of the investment rate on the growth rate, whereas q depends on the number of periods of lead and lag within which the disturbance term is correlated with the investment rate. The lag length in $D'(L)$ equals the larger of p and q .

Jones (1995) used a different empirical procedure to estimate the long-run effect of the investment rate on the growth rate. His procedure can be expressed as²⁵

$$g_t = A(L)g_{t-1} + B(L)x_t + \epsilon_t. \quad (3.10)$$

Two main problems affect the estimation of the long-run relation between the growth and investment rates in the form of equation (3.10). First, as discussed above, the disturbance term ϵ_t is likely to be correlated with the current and lagged values of investment rate.²⁶ Second, ϵ_t is also likely to be serially correlated, thus it may be

²⁵ Equation (3.10) can be seen as a special case of the transfer function model, which has a general form

$$A(L)y_t = \gamma + B(L)x_t + C(L)\epsilon_t,$$

where the disturbance terms are represented as an *MA* process (see Harvey 1990, chapter 7). The polynomial $B(L)$ is called a transfer function because it shows how a movement in the exogenous variable x affects the time path of (i.e., is transferred to) the endogenous variable y .

²⁶ Jones (1995) dealt with this problem indirectly, using an extreme-bounds technique.

correlated with the autoregressive terms $A(L)g_{t-1}$. These two problems will result in an inconsistent estimate of $B(1)$. But they can be avoided by using the procedure expressed in equation (3.9).

An additional problem with equation (3.10) is that it has no constant term. But with a positive depreciation rate δ^* and population growth rate n , the AK model implies that the growth rate is negative when the investment rate is 0, as is evident in equation (2.7). Thus, I include a constant term in equation (3.9) to reflect the true spirit of the AK model.

3.2. Time-Series Tests Using the Post-War Data

In the tests of the one-sector model in this chapter, as well as the tests of the two-sector model in Chapter 5, I use time-series data for OECD countries only. This is intended to take advantage of the better availability and higher reliability of annual time-series data, to avoid confounding possible differences in the processes of growth in developing and developed countries, and to ensure that my findings are closely comparable with those of existing studies. Presently, the OECD has 29 member countries. Because the data are available only up to 1992, I exclude from the sample the five countries that joined OECD after 1992: the Czech Republic, Hungary, Korea, Mexico and Poland. This gives me a sample of 24 OECD countries. In the tests using the post-war data, I first focus on the 15 countries examined in Jones' (1995) study, then extend the tests to the other nine countries in the sample.

According to the AK model, the long-run effect of the investment rate on the growth rate is positive. This implies a hypothesis for equation (3.9), i.e., $B(1) > 0$. I estimate equation (3.9) with four leads and lags of Δx for the 15 OECD countries selected by Jones (1995) and summarize the key results in Table 3.1. The results are, however, very robust to the choice of the length of leads and lags. For instance, varying the length of leads and lags from 2 to 6 — a range broad enough to embrace a typical business cycle²⁷ — causes no noticeable change in the sign, magnitude or the levels of significance of the estimated coefficients.²⁸

Because in equation (3.9) the disturbance term is uncorrelated with the independent variables, consistent estimates of the parameters can be obtained by using least-squares estimators. But, as is common in a time-series setting, the disturbance term is likely to be serially correlated. As such, the standard errors of the coefficients conventionally estimated by the least-squares estimators are likely to be biased and inconsistent.²⁹ To correct this bias in estimates of the standard errors, I use the Newey–West (1987) estimator of the covariance matrix of the disturbance term, which is heteroscedasticity and autocorrelation consistent.

²⁷ National Bureau of Economic Research (NBER) Official Business Cycle Dates show that the average US peace-time business-cycle duration is 48 months (see United States, Department of Commerce 1994).

²⁸ See, for example, Table A3.1 for the results of regression with five leads and lags of the first difference of investment rate.

²⁹ If the autocorrelation is positive, as in most economic time series, the standard errors of coefficients estimated by least-squares estimators are usually too small (see Greene 1993; p. 422).

Column 2 in Table 3.1 shows that the estimate of the long-run effect of the investment rate on the growth rate is positive and that it differs significantly from zero at 5% level (i.e., $p \leq 0.05$) in eight of 15 countries. Although the long-run coefficient has the wrong sign in three countries, in none of them is the coefficient significantly negative. For the eight countries where the estimated long-run coefficient is significantly positive, the magnitude of the coefficient is rather similar: a one percentage point increase in the investment rate is associated with one quarter to one (0.21–0.92) percentage point increase in the growth rate.

The values of adjusted R^2 indicate that the long-run effect, together with short-run dynamics, of the investment rate explains 57–92% of the total variation in the growth rate in all 15 countries except Norway. This goodness of fit is remarkable, considering that the model has only one independent variable — i.e., the investment rate — and the leads and lags of its first-difference term.

Durbin–Watson statistics in the last column indicate that serial correlation is a problem in a majority of countries in the sample. So, the correction for serial correlation using the Newey–West estimator is indeed necessary. The Newey–West t -statistics reported in the table are based on the assumption of $AR(1)$ disturbance terms, but allowing higher orders of autocorrelation makes little difference to the estimated standard errors.

The results reported in Table 3.1 differ substantially from those found in Jones' (1995) study. Based on his specification, expressed in equation (3.10), and the PWT5 data set, Jones found no evidence for $B(1) > 0$ for the 15 OECD countries, and several of

Table 3.1 Long-run effect of the investment rate on the growth rate in 15 OECD countries, 1950–1990^a

Model:			
$g_t = a + B(1)x_t + \sum_{k=4}^4 d_k \Delta x_{t-k} + v_t$			
Country	Long-run effect ^b B(1)	Adjusted R ²	Durbin–Watson statistics
Australia	0.463*** (3.304)	0.745	1.427
Austria	-0.184 (-1.129)	0.618	1.000
Belgium	0.463*** (3.145)	0.706	1.441
Canada	-0.085 (-0.271)	0.613	1.144
Denmark	0.009 (0.169)	0.840	1.631
Finland	0.201 (1.596)	0.569	1.682
France	0.207** (2.218)	0.647	0.856
Germany	0.466*** (8.345)	0.916	0.929
Italy	0.538*** (7.101)	0.857	1.201
Japan	-0.028 (-0.360)	0.657	1.533
Netherlands	0.476*** (5.842)	0.820	1.753
Norway	0.052 (0.254)	-0.171	1.380
Sweden	0.270*** (3.984)	0.767	2.014
United Kingdom	0.046 (0.353)	0.739	1.213
United States	0.919** (2.315)	0.748	1.750

Note: ^a The coefficients and t-statistics for the leads and lags of the first-difference term of the independent variable are not reported in the table here and throughout this paper.
^b t-statistics calculated from the Newey–West estimators are reported in parenthesis, here and throughout the tables in this chapter.

his estimates produced $B(1)$ significantly less than zero.³⁰ Since Jones' tests and mine differ in both data sources and the empirical specification, it would be interesting to see how much of the difference in the results can be attributed to the difference in the data source and how much to that in the empirical specification. For this purpose I run regressions of my specification, expressed in equation (3.9), with Jones' data set, and report the results in Table 3.2. A comparison between the results reported in Table 3.1 and those in Table 3.2 shows that the difference in data sources cause no essential difference in the regression results in a vast majority of the 15 countries. For instance, while $B(1)$ is significantly positive in eight countries in Table 3.1, it remains significantly positive in six of these eight in Table 3.2. The only major difference that the change in data source makes is in the United States; i.e., $B(1)$ for the United States is significantly positive in Table 3.1, but significantly negative in Table 3.2. However, a data error is found in the investment rate for the United States in PWT5, and the error could account for the difference in the regression results.³¹ As the regression results reported in Table 3.2 seem to be very close to those shown in Table 3.1 but quite different from those found in Jones' (1995) study, I believe that the difference between the long-run effect of the investment rate estimated in this study and that estimated by Jones (1995) is due

³⁰ However, as Jones (1995) did not show the regression results, I cannot compare his estimates with mine.

³¹ See Figure A2.1, in the Appendix II, for the difference in the investment rates for the United States in the two data sets. The errors in the US investment rate in PWT5 were corrected in PWT5.6.

Table 3.2 Long-run effect of the investment rate on the growth rate in 15 OECD countries, using Jones' (1995) data set, 1950–1988 ^a

Model:			
$g_t = a + B(1)x_t + \sum_{k=4}^4 d_k \Delta x_{t-k} + v_t$			
Country	Long-run Effect ^b B(1)	Adjusted R ²	Durbin–Watson statistics
Australia	0.751*** (5.365)	0.693	2.198
Austria	-0.191 (-1.059)	0.719	1.261
Belgium	0.301 (1.453)	0.606	1.451
Canada	-0.704* (-1.758)	0.007	2.282
Denmark	-0.113 (-1.279)	0.791	1.764
Finland	0.052 (0.385)	0.530	1.608
France	0.158 ** (2.173)	0.806	1.437
Germany	0.539*** (5.178)	0.834	1.585
Italy	0.518*** (5.503)	0.882	0.587
Japan	0.081* (1.712)	0.774	2.107
Netherlands	0.482*** (4.391)	0.676	2.042
Norway	-0.249 (-1.512)	-0.033	2.152
Sweden	0.188* (1.701)	0.667	2.335
United Kingdom	-0.002 (-0.025)	0.804	1.190
United States	-0.926*** (-4.383)	0.751	1.568

Note: ^a The data set, based on PWT5, is provided by Jones.

^b *, **, *** indicate significant at 10%, 5% and 1% levels, respectively.

primarily to the differences in empirical specifications.³² The correlation between the disturbance term and the explanatory variables, which exists in Jones' specification expressed in equation (3.10), may be partly responsible for the negative long-run effect of investment found in his study.

It is interesting to compare the results in Table 3.1 with the time trends in Table 2.1. While the estimates of long-run effects of the investment rate on the growth rate reflect the dynamic relation between the two series for the entire sample period, the time-trend regressions simply fit the growth and investment rates with straight lines, and they take no account of possible long swings or nonlinear trends in the variables. This methodological difference in the two tables can help to explain why the long-run effect of investment rate has a positive sign in Denmark, France and the United Kingdom, despite the fact that the time trends for the investment and growth rates in these countries have different signs. The results of the time-series regressions reported in Table 3.1 provide more convincing evidence of a positive linkage between investment and growth rates and therefore support the *AK* model of endogenous growth.

The 15 OECD countries in Tables 2.1, 3.1 and 3.2 are selected to facilitate comparison with the sample in Jones' (1995) study. One can as well estimate the long-run effect of investment for the remaining OECD countries in the sample. Table 3.3 shows that the OLS results based on equation (3.9) for the other nine OECD countries are quite

³² Jones kindly provided me with the data set he used in his paper, and this enables me to run a regression of equation (3.9) based on his data. But I do not have the exact empirical specification of his individual-country regressions; thus, I am unable to replicate his tests with new data based on PWT5.6.

similar to those reported in Table 3.1. The long-run effect of the investment rate is positive in seven of these nine countries, and it is significantly positive in three. In not a single country is the long-run effect of the investment rate significantly negative.

Table 3.3 Long-run effect of the investment rate on the growth rate in nine OECD countries, 1950–1990

Model:			
$g_t = a + B(1)x_t + \sum_{k=4}^4 d_k \Delta x_{t-k} + v_t$			
Country	Long-run Effect $B(1)$	Adjusted R^2	Durbin–Watson statistics
Greece ^a	0.420*** (5.696)	0.580	2.171
Iceland	0.143 (0.661)	0.396	1.470
Ireland	0.143* (1.972)	0.630	1.757
Luxembourg	0.125 (1.560)	0.550	1.436
New Zealand	0.856*** (3.580)	0.383	2.225
Portugal ^b	0.057 (0.276)	0.276	1.247
Spain	0.198 (1.667)	0.560	0.822
Switzerland	-0.084 (-0.524)	0.681	1.411
Turkey	-0.079 (-0.294)	0.102	2.011

Note: ^a 1950–1991.

^b 1950–1990.

3.3. Time-Series Tests Using Annual Data for More Than a Century

The time series of annual data in the post-war era may not be long enough to reveal the long-run relationship between growth and investment rates. The main concern is the lack of degrees of freedom.³³ Indeed, the lack of degrees of freedom may to some extent account for the result that $B(1)$ is not significantly different from zero for about one half of those 24 OECD countries reported in Tables 3.1 and 3.3. I address the degrees-of-freedom problem in two ways. First, I use the Maddison data set on investment and growth rates to examine the relationship between the two variables for more than a century, starting as early as 1870, for six major developed countries. Second, I run pooled regressions for the 24 countries in the sample, assuming equality of the long-run effect of the investment rate on the growth rate in all 24 countries or within certain subgroups. Each approach has its advantages and disadvantages. The advantage of the first approach is that using time-series data for more than a century provides the model with more degrees of freedom and more variability. The disadvantages are: (1) structural breaks and parameter changes during the long sample period could limit the applicability of the model; and (2) the further back one goes in the history, the more difficulties one is likely to face in terms of availability and reliability of the data. Pooled regression is an effective way to address the degrees-of-freedom problem without introducing the problems with structural

³³ The annual data are available for 1950–1990, but a great loss of degrees of freedom is caused by including the leads and lags of the first difference of the investment rate in the estimating procedure. For instance, the degrees of freedom were reduced to 23 after adding four leads and lags of the first difference of investment rate to the regression.

breaks and parameter changes. The benefits of pooled regression come, however, at a cost: the assumption of equal long-run effects across countries may be problematic because of the heterogeneity of the OECD countries in the sample. Pooled time-series regressions are discussed in the next section.

As shown in Figure 2.1, one main problem with using long time series is that the two world wars had tremendous impacts on the behaviour of the investment and growth rates, causing wild swings especially in the growth rates, during the war times and the reconstruction periods following the wars. One way to control for the impacts of the wars is to exclude war periods from the sample. Reported in Table 3.4 are the key results of estimating equation (3.9) for Australia, Canada, France, Japan, the United Kingdom, and the United States for 1870–1987, excluding the war years (i.e., 1914–1919 and 1939–1945).³⁴ The long-run multiplier of the investment rate has a positive sign in all six countries, and it is significantly positive in four. These results provide stronger support for the *AK* model than those based on post-war data. One especially noteworthy change occurs in the estimate for Japan, where the post-war regression gives a negative estimate of the long-run effect of the investment rate, but the century-long time-series regression produces a positive and significant estimate. The increase in data points also lead to more efficient estimates of the long-run multipliers in Australia, France and the United Kingdom, as the standard errors of the coefficients are much smaller for these countries in

³⁴ The sample period for Japan is 1885–1987. The years excluded from the sample for France are 1914–1921 and 1939–1950, because Maddison (1991a) data on the investment rate for France during these years were unavailable. This is also why the Hodrick–Prescott trends in the investment and growth rates for France were not reported in Figure 2.1.

Table 3.4 than those for the same countries in Table 3.1.

Table 3.4 Long-run effect of the investment rate on the growth rate in six major developed countries, 1870–1987 ^a

Model:			
	$g_t = a + B(1) i_t + \sum_{k=4}^4 d_k \Delta i_{t-k} + v_t$		
Country	$B(1)$	Adjusted R^2	Durbin–Watson statistics
Australia	0.170** (2.838)	0.218	2.001
Canada	0.101 (0.977)	0.382	2.185
France	0.319*** (5.437)	0.404	2.185
Japan ^b	0.234*** (3.682)	0.251	2.299
United Kingdom	0.091* (1.671)	0.120	2.402
United States	0.156 (0.525)	0.165	2.186

Note: ^a Excluding the years during the two world wars (i.e., 1914–1919 and 1939–1945), except for France, where 1914–1921 and 1939–1950 are excluded.
^b 1885–1987.

Another way to control for the impacts of the wars on the estimates of long-run multipliers is to use dummy variables for 1910–1950, which includes the two world wars and the inter-war years with special economic problems such as the Great Depression. The regression results of the dummy-variable method (reported in Table A3.2, in Appendix III) differ little from those reported in Table 3.4.

3.4. Panel-Data Tests of the One-Sector Model

The panel-data approach to empirical testing of growth theories recently received considerable attention in the literature.³⁵ Because panel data comprise observations of a cross-section of units (countries, firms, or households, etc.) over time, they provide more degrees of freedom, greater variability and lesser collinearity among variables than single time-series or single cross-sectional data sets. Panel data also allow researchers to make inferences about dynamic behaviour and cross-sectional differences in the same model.³⁶ Generally speaking, a panel data set has two dimensions — length (i.e., the number of time periods) and width (i.e., the number of units) — and therefore two types of heterogeneity — intertemporal and cross sectional. Long and narrow panels — i.e., those containing data on a few units over a long period — are often referred to as pooled-time-series data sets; short and wide panels — i.e., those containing data on a very large number of units over a short period — are sometimes referred to as longitudinal data sets.³⁷ Different types of panel data require different analytical approaches. For example, the analysis of pooled-time-series data often emphasizes the time dimension by controlling for cross-sectional heterogeneity, whereas the analysis of longitudinal data tends to focus on the cross-sectional heterogeneity.

³⁵ See Coe and Helpman (1995) and Islam (1995), for example.

³⁶ See Baltagi (1995, pp. 3–7) for benefits and limitations of panel-data analysis.

³⁷ See Greene (1993, chapter 16).

The panel of annual data for 24 OECD countries during 1950–1990 can be viewed as a pooled-time-series data set. To use this data set to test the one-sector AK model, I re-write equation (2.7), which determines the long-run growth rate, as a general pooled-time-series data model:

$$g_t^i = \alpha^i + B^i(L) x_t^i + \varepsilon_t^i, \quad i = 1, \dots, 24, \quad (3.11)$$

where superscript i identifies a country or a group of countries in the panel of 24 countries; α^i denotes the time-invariant country-specific (or group-specific) intercept; and ε_t^i is the disturbance term, which varies across countries and over time. In the context of the one-sector AK model, variations in intercepts can result from differences in underlying parameters — such as the depreciation rate and population (or labour-force) growth rates — across countries or from country-specific measurement errors in growth and investment rates.

As in the single-country regression model, ε_t^i reflects cyclical shocks in each economy in the pooled-time-series-data model; thus, it is highly possible that ε_t^i is correlated with x_t^i at time t and serially correlated over time in country i . Using the procedure developed for the single-country time-series regression model, I take the correlation between ε_t^i and x_t^i into account by augmenting the pooled regression with leads and lags of the first difference of the investment rates, and I re-write equation (3.11) as

$$g_t^i = \alpha^i + B^i(1) x_t^i + D^{ii}(L) \Delta x_{t,p}^i + v_t^i, \quad (3.12)$$

where v_t^i is uncorrelated with x_t^i and Δx_t^i .

An important issue in pooled-time-series-data analyses is accounting for parameter heterogeneity among countries. Because parameter heterogeneity may take the form of variations in intercepts or slope coefficients, or both, I consider the following four cases, corresponding to four sets of restrictions on the intercepts and the short- and long-run slope coefficients in equation (3.12):

- (1) All intercepts and long- and short-run slope coefficients are the same across countries, i.e., $\alpha^i = \alpha$, $B^i(I) = B(I)$ and $D^i(L) = D'(L)$;
- (2) Intercepts and long-run slope coefficients are the same, but short-run slope coefficients differ, i.e., $\alpha^i = \alpha$, $B^i(I) = B(I)$ and $D^i(L) \neq D'(L)$;
- (3) Long-run slope coefficients are the same, but intercepts and short-run slope coefficients differ, i.e., $\alpha^i \neq \alpha$, $B^i(I) = B(I)$ and $D^i(L) \neq D'(L)$; and
- (4) Intercepts, as well as long- and short-run slope coefficients differ, i.e., $\alpha^i \neq \alpha$, $B^i(I) \neq B(I)$ and $D^i(L) \neq D'(L)$.

An issue related to cross-country parameter heterogeneity is whether the variations in intercepts and slope coefficients are to be thought of as fixed or random. In general, the fixed-coefficients model is an appropriate specification if the focus of the model is on a specific set of units and the inference is restricted to (or conditional on) the behaviour of this set of units. The random-coefficients model is an appropriate specification if the sample is drawn randomly from a population and the inference pertains to the population from which the sample was drawn.³⁸ For this study, the fixed-coefficients model is a better choice because, first, the panel is not a random sample of OECD countries but

³⁸ See Hsiao (1975, pp. 41–48 and pp. 128–138) and Baltagi (1995, pp. 9–18).

contains all countries that became OECD members before 1992. Second, a random-coefficients model assumes that the country-specific effects are independent of other regressors in the model. But if country-specific measurement errors occur in growth and investment rates, then the country-specific effects are highly possible to be correlated with the regressors, contrary to the assumption of the random-effects model. Indeed, the fixed-coefficients model is the usual choice of macroeconomists.³⁹

Another major issue in pooled-time-series regression models is possible cross-sectional heteroscedasticity and correlation of the disturbance terms. The pooled regressions of growth rates on investment rates in OECD countries are no exception. On the one hand, because OECD countries differ in their sizes and in their growth and investment rates, they may also differ in the variances of the residuals from the regressions of growth rates on investment rates. On the other hand, because the disturbance term captures cyclical effects in each country, and it is well documented that the business cycles in OECD countries are closely linked, it is reasonable to expect a contemporaneous correlation of disturbance terms across countries. Therefore, the least-squares estimators of the pooled regressions would be inefficient because they take no account of the possible cross-country heteroscedasticity and correlation of the disturbance terms. To address this concern, I also use Seemingly Unrelated Regression (SUR) estimators for the long-run multipliers in all the four cases. The restrictions in each case are imposed by assuming the equality of the relevant coefficients across equations in the SUR estimators. I report the results from both OLS and SUR estimators in the discussion of these four cases.

³⁹ See Islam (1995) and Judson and Owen (1996), for example.

As in single-time-series regressions, in each of the four cases discuss below I use four leads and lags of the first-difference term of the investment rate to augment the OLS and SUR estimators. The estimates are, however, very robust to changes in the number of leads and lags of the first-difference term included in the regressions.⁴⁰

Case 1: $\alpha^i = \alpha$, $B^i(1) = B(1)$ and $D^i(L) = D'(L)$

Case 1 is the most restricted and the simplest case of pooled-time-series regressions. It assumes that intercepts, long-run effects and short-run dynamics are all equal across countries. This case is often referred to as the simple pooled-time-series regression, or the common-intercepts model. Table 3.5 gives the key results from both OLS and SUR estimators for this case.

Just as the *AK* model predicts, the long-run multipliers of the investment rates are significantly positive. Two points merit further comment. First, the estimated long-run coefficients are considerably smaller than those found in the countries where the individual-time-series regressions give significantly positive estimates of the multipliers. This phenomenon is not surprising because pooled-time-series regressions impose a common long-run multiplier on all countries in the panel. If the true long-run multipliers differ among countries in the panel, the estimates using the panel data will naturally underestimate the long-run multipliers for some countries and overestimate them for others. Second, the pooled regressions explain a considerably smaller proportion of the

⁴⁰ Table A3.3, in Appendix III, reports OLS estimates with the number of lag terms in the varying from 4 to 8. The regression results are robust to these variations.

Table 3.5 Results of pooled regressions for 24 OECD countries, one-sector model, 1950–1990, Case 1

	OLS	SUR
a	0.047 (0.084)	0.006 (0.027)
$B(1)$	0.102*** (4.822)	0.096*** (11.418)
Adjusted R^2 ^a	0.430	—
Standard error of regression ^{a, b}	2.416	—

Note: ^a The adjusted R^2 and the standard error of the SUR estimator are not available.

^b The standard error of the OLS regression is scaled up by 100 here and throughout the thesis.

variations in the data than the single-time-series regressions do. The adjusted R^2 of the OLS regression is less than 50%, which is significantly lower than most of its counterparts in the single-time-series regressions. This is because the panel data include variations over time, as well as over countries. Making the intercepts and slope coefficients equal across countries inevitably reduces the goodness of fit.

Case 2: $\alpha^i = a$, $B^i(1) = B(1)$ and $D^i(L) \neq D'(L)$

The short-run slope coefficients, $D'(L)$, tend to reflect each country's specific dynamic behaviour, such as the timing and the responsiveness of its growth rate to a change in the investment rate. Therefore, it would be too restrictive to assume that the short-run slope coefficients are equal across countries. In this case, I relax this assumption by allowing the short-run slope coefficients to vary from country to country.

Table 3.6 shows the key results from the OLS and SUR estimators under the assumption that the intercepts and long-run coefficients are the same but the short-run coefficients vary across OECD countries. Two points are worth noting. First, the estimated long-run multiplier of investment rate is significantly positive, and its magnitude is compatible with that found in the previous case. Second, allowing the short-run effects to differ across countries significantly improves the goodness of fit of the OLS regression, as shown in the value of the adjusted R^2 , the standard error of regression, and the F -statistics. This finding confirms the prior information about the cross-country differences in dynamic behaviour of growth and investment rates.

Table 3.6 Results of pooled regressions for 24 OECD countries, one-sector model, 1950–1990, Case 2

	OLS	SUR
α	-0.212 (-0.442)	-1.647*** (-12.275)
$B(1)$	0.109*** (6.034)	0.091*** (15.430)
Adjusted R^2	0.495	—
Standard error of regression	2.274	—
F -test for common short-run coefficients ^a	1.484***	—

Note: ^a The F -test uses the OLS regression in Case 1 as the restricted regression.

Case 3: $\alpha^i \neq \alpha$, $B^i(1) = B(1)$ and $D^i(L) \neq D'(L)$

The intercept terms in equation (3.12) reflects depreciation and population growth rates in the *AK* model. It can be argued that the depreciation rates and population growth rates vary with levels of economic development.⁴¹ Despite the generally perceived homogeneity, the levels of economic development obviously differ among OECD countries.⁴² Therefore, it is worthwhile exploring whether the intercept terms reflect these differences. To this end, I divide the 24 OECD countries into three groups, according to levels of economic development. The first group comprises the seven largest and most developed countries — Canada, France, Germany, Italy, Japan, the United Kingdom and the United States (often referred to as the G7 countries). The second group comprises of the nine small and medium sized developed countries — Australia, Austria, Belgium, Finland, Luxembourg, Netherlands, Norway, Sweden and Switzerland. The third group consists of the remaining eight countries in the sample — Denmark, Greece, Iceland, Ireland, New Zealand, Portugal, Spain and Turkey.⁴³ This group comprises the least-advanced economies in the sample.

The key results of the pooled-time-series regressions with group-specific

⁴¹ See Table A2.2 for the average population growth rates in OECD countries.

⁴² One indication of the heterogeneity of OECD countries is the difference in labour productivity. As it is shown in Table A2.3, in 1990 the labour productivity (measured by real GDP per worker) in the United States was more than twice as high as that in Greece and Portugal and more than four times as high that in Turkey.

⁴³ The allocation of countries to the second and third groups is based on their levels of labour productivity in 1990. See Table A2.3 for a rank of real GDP per worker in these 24 countries.

intercepts, country-specific short-run coefficients, and a common long-run coefficient are reported in Table 3.7. The main finding worth emphasizing is that allowing group-specific intercepts does not change the sign and magnitude of the estimated long-run multipliers of the investment rate. The estimated $B(1)$ remains positive and significant, with a magnitude compatible with that in the previous cases. The results suggest some differences in intercepts among the three groups, as the F -statistics reject the null hypothesis that the intercepts are identical across the three groups.⁴⁴

Table 3.7 Results of pooled regressions for 24 OECD countries, one-sector model, 1950–1990, Case 3 ^a

	OLS	SUR
α_1	-0.786* (-1.688)	-0.828*** (-2.704)
α_2	-1.156** (-2.223)	-1.100*** (-3.189)
α_3	-0.409 (-0.820)	0.038 (0.109)
$B(1)$	0.130*** (7.049)	0.118*** (8.395)
Adjusted R^2	0.504	—
Standard error of regression	2.254	—
F -statistics for common intercept ^b	5.171***	—

Note: ^a α_1 , α_2 and α_3 stand for the intercepts of the three groups of countries, respectively.

^b The F -test uses the OLS regression in Case 2 as the restricted regression.

⁴⁴ t -statistics also reject the null hypothesis. In the OLS regressions, for example, the t values for the difference between α_1 and α_2 and that between α_2 and α_3 are 2.086 and 3.504, respectively, and both exceed the critical t value at the 5% level.

Case 4: $\alpha^i \neq \alpha$, $B^i(I) \neq B(I)$ and $D^i(L) \neq D'(L)$

The long-run effect of investment on growth depends on the level of technology and the ratio of physical to human capital. Therefore, it can be hypothesized that this effect is higher in technologically more advanced countries (i.e., the G7 countries in the first group) than in less advanced countries (i.e., countries in the second and third groups). I test this hypothesis by letting the long-run coefficients of investment rates differ among the three groups, and report the results in Table 3.8. Three findings are worth noting.

First, the long-run multipliers of investment rates for the three groups of OECD countries are significantly positive (except for the OLS estimate for the third group), and the sizes of the coefficients are compatible with that estimated in the three previous cases.

Second, there are some indication that the long-run multiplier of the first group (i.e., the G7 countries) may be larger than those of the other two groups, but the evidence is not overwhelming. The *t*-tests for the null hypothesis of identical long-run coefficients between groups are inconclusive, as shown below.

Hypotheses	OLS	SUR
$B(I)_1 = B(I)_2$	1.638	3.153***
$B(I)_1 = B(I)_3$	1.728*	0.491
$B(I)_2 = B(I)_3$	0.826	2.616***

And third, allowing the long-run multipliers to differ in the estimation only slightly improves the goodness of fit, as can be seen from the *F*-statistics, which reject only marginally the null hypothesis of common long-run coefficient.

Table 3.8 Results of pooled regressions for 24 OECD countries, one-sector model, 1950–1990, Case 4

	OLS	SUR
a_1	-2.059*** (-2.723)	-2.836*** (-5.354)
a_2	-0.796 (-1.258)	-0.436 (-0.853)
a_3	1.202 (0.806)	0.124 (0.119)
$B(1)_1$	0.181*** (5.868)	0.198*** (8.922)
$B(1)_2$	0.118*** (5.093)	0.092*** (4.568)
$B(1)_3$	0.065 (1.090)	0.114*** (2.705)
Adjusted R^2	0.507	—
Standard error of regression	2.247	—
F -statistics for common long-run coefficients ^a	2.635*	—

Note: ^a The F -test for common-long-run-coefficient uses the OLS regression in Case 3 as the restricted regression.

I also tested specifications of country-specific intercepts and short-run slope coefficients with and without the restriction of common long-run slope coefficient. As reported in Table A3.4, results differ little from those of the group-specific-intercept specification, reported in Tables 3.7 and 3.8.

It can be seen from Tables 3.5–3.8 that in general the SUR estimators give the

similar magnitude higher t values for the long-run coefficients than those given by the OLS estimators. These results indicate cross-country heteroscedasticity and correlation in the data, as well as confirming a well-known econometric theorem, i.e., that with cross-sectional heteroscedasticity and correlation in the disturbance terms, an OLS estimator provides consistent, though inefficient, estimates of coefficients. Without doubt SUR estimators generate better estimates of the long-run coefficients.

The estimated long-run multipliers of investment rates reported in Tables 3.5–3.8 are robust to changes in the sample period and in the number of countries included in the panel. For example, Table A3.5 shows that the OLS estimators for a panel of 22 OECD countries for 1967–1985 give results similar to those reported in Tables 3.5 and 3.6.⁴⁵

3.5. Summary

To implement the time-series test of the AK model, I adopt an new procedure to account for the correlation between the independent variables and the disturbance terms arising from cyclical shocks in the economy. I then use two different data sets for OECD countries to test the model. The main results of the tests are as follows.

First, individual-country time-series regressions for 24 OECD countries, using Penn World Table (Mark 5.6) data for 1950–1990, produce evidence supporting a positive long-run effect of the investment rate on the rate of growth. The estimated long-

⁴⁵ The tests of two-sector endogenous growth models discussed in the following chapters are based on this panel.

run multiplier of the investment rate is significantly positive in 12 of the 24 OECD countries. Although the multiplier has the wrong sign in five countries, in no case is it significantly negative. These results cast doubt on a key finding of Jones (1995) that the investment rate had no positive long-run effect on the growth rate in OECD countries in 1950–1988. The tests of the *AK* model in this study and those in Jones (1995) differ in both data sources and empirical procedures, but the difference in testing results arise primarily from the differences in empirical testing procedures.

Second, the time-series tests using the Maddison data set on growth and investment rates during 1870–1987 for six main OECD countries reveal that the investment rate has a significantly positive long-run effect on the growth rate in four of these six countries. This finding greatly strengthens the results of individual-country time-series regressions.

Third, tests using pooled-time-series data for 24 OECD countries from 1950 to 1990 produce further evidence for the positive long-run linkage between the rates of investment and growth. Estimates of the long-run effect based on both OLS and SUR estimators are significantly positive in all four cases, which range from the simple pooled-time-series specification to the variable-intercept and variable-coefficient specifications. The variable-long-run-coefficients case also reveals that the long-run effects of investment rate are positive in each of the three groups of OECD countries at different levels of technological and economic development, and the effects seem to be similar among these groups.

CHAPTER 4

TWO-SECTOR ENDOGENOUS GROWTH MODELS

4.1. Introduction

In Chapters 2 and 3, I establish that, contrary to Jones' (1995) findings, significant evidence supports the one-sector AK model. Time-series and panel-data evidence from OECD countries is consistent with the empirical implications of the model.

Yet, all is not right for the AK model. There is considerable scepticism about the model. This is partly because the model employs a simple linear production function, with no non-reproducible factors and therefore no diminishing returns to capital accumulation. Also the model has a simple one-sector structure. Although the model interprets capital in a broad sense as including physical and human capitals, it treats the physical and human capitals equally, assuming that the one-sector technology applies to the production of both physical and human capitals. Moreover, as a consequence of the one-sector structure and non-diminishing returns, the model lacks transitional dynamics: no matter where it begins, the economy immediately exhibits the steady state; any shock to the economy will instantly push it to a new steady state. The model allows no transitional path between different

steady states.

Because of these features, the AK model implies that the ratio of physical to human capital is constant over time, i.e., $\omega = \alpha/(1-\alpha)$. The model is unable to accommodate any change in the ratio of the two types of capital as the economy evolves. This is inconsistent with the observed upward trends in the ratio of physical to human capital in OECD economies. As shown in Figure 4.1, this ratio steadily increased in the G7 countries during 1965–1987. One plausible explanation for this is that these economies

Figure 4.1. The ratio of physical to human capital in the G7 countries, 1965-1987

Source: Physical-capital-stock data are from PWT5.6; human-capital-stock data are from Nehru et al. (1995).

are not in their steady state but in a transition period.⁴⁶ Ignoring the dynamic behaviour of the ratio of physical to human capital may seriously undermine the accuracy of the estimated long-run effect of the investment rate on the growth rate. This is possible for two reasons. First, if the ratio of physical to human capital changes over time, then it may have an independent effect on the growth rate. Thus, failing to include the ratio in the regression model may lead to an omitted-variable error. Second, in the empirical relation derived from the *AK* model, the ratio of the two capitals is a determinant of the coefficient that represents the effect of the investment rate on the growth rate.⁴⁷ Consequently, if the ratio is not constant, then neither is the coefficient. The assumption that the coefficient is constant biases the result.

Extending the tests of endogenous growth hypothesis beyond the *AK* model, this chapter derives an hypothesis from two-sector extensions of the *AK* model, namely, the Lucas (1988) model and its variants.⁴⁸ I start with a basic version of the model, in which physical capital plays no role in the production function of human capital. Then I move on to the model with externalities associated with human capital. In the end, I discuss the generalized version of the model developed by Rebelo (1991), which brings physical capital into the production functions in both sectors. Detailed treatments of these models

⁴⁶ Alternative explanations for the increase in the ratio and measures of human capital stocks are discussed in details in Chapter 5.

⁴⁷ See equation (2.6), in Chapter 2.

⁴⁸ Because the model in Lucas (1988) is based on that in Uzawa (1965), it is sometime also referred to as the Uzawa–Lucas model. See Barro and Sala-i-Martin (1995), for example.

can also be found in Mulligan and Sala-i-Martin (1993), Barro and Sala-i-Martin (1995) and Faig (1995).

4.2. The Basic Lucas Model

The basic Lucas model has two sectors: final-goods and human-capital production (or education). Following Barro and Sala-i-Martin (1995), I specify the model as

$$\text{Max} \int_0^{\infty} \exp(-\rho t) \frac{c_t^{1-\theta} - 1}{1-\theta} dt, \quad (4.1)$$

subject to

$$\dot{c}_t = y_t - \dot{k}_t - \delta k_t, \quad (4.2)$$

$$y_t = A k_t^{\alpha} (u_t h_t)^{1-\alpha}, \quad (4.3)$$

$$\dot{h}_t = B (1 - u_t) h_t - \delta h_t, \quad (4.4)$$

where ρ is the rate of time preference; θ is the inverse of the intertemporal elasticity of substitution; c_t is the per capita consumption; y_t is per capita output of final-goods; k_t and h_t are per capita physical- and human-capital stocks; u_t is the fraction of human-capital stock used in final-goods production; δ is the common depreciation rate of physical- and

human-capital stocks;⁴⁹ and A and B are positive constants representing the levels of technology in the two sectors (i.e., A determines the productivity level in the final-goods sector, and B determines the rate of returns in human-capital accumulation).

Output can be used on a one-for-one basis for consumption or for investment in physical capital but not for investment in human capital. In Lucas (1988), an individual's human-capital stock is simply his or her skills level, so that a worker with one unit of human capital is a productive equivalent of two workers each with one-half unit of human capital. In other words, human capital and labour are perfect substitutes. The production of human capital is assumed to use human capital only. Because B is constant, there are no diminishing returns to human-capital accumulation; i.e., the rate of increase in human-capital stock is proportional to the effort devoted to the human-capital accumulation, no matter what level of human-capital stock has already been attained.

In equations (4.1)–(4.4), parameters ρ and θ represent the consumers' taste, or preference, whereas A , B , α and δ specify the technology in the economy. The model has two control variables: consumption, c_t , and the proportion of human capital devoted to final-goods production, u_t . The representative consumer has to make two decisions: a choice between current and future consumption, and an allocation of time between final-goods production and human-capital accumulation, such as schooling.

The broad output of the economy, which is the sum of total gross output from the two sectors, can be defined as

⁴⁹ Without losing generality, I assume that the physical and human capital have the same depreciation rate to simplify the notation. Likewise, the rate of population growth is assumed to be zero.

$$z_t = y_t + \frac{\mu}{\nu} B (1 - u_t) h_t, \quad (4.5)$$

where z_t is per capita broad output, μ and ν are the shadow prices of the final goods and human capital, respectively.

4.2.1. The steady-state solution

The steady state (or balanced growth path) is defined as a state in which all variables grow at a constant (possibly zero) rate and in which they have no inherent tendency to divert from this state. In the steady state of the basic Lucas model, the physical- and human-capital stocks grow at the same constant rate. Therefore, it is convenient, as well as conventional, to analyze the model in terms of variables that remain constant in the steady state. Recalling that ω_t is the ratio of physical to human capital (i.e., $\omega_t = k_t/h_t$), and defining the investment rate, i_t , as the fraction of final goods not consumed (i.e., $i_t = 1 - c_t/y_t$), then, as I show in the Appendix I (A), the steady-state solutions of the basic Lucas model can be expressed as the following equations for variables ω_t , u_t and i_t :

$$\omega^* = \left(\alpha \frac{A}{B}\right)^{\frac{1}{1-\alpha}} \left[\varphi + \frac{\theta-1}{\theta}\right], \quad (4.6)$$

$$u^* = \varphi + \frac{\theta-1}{\theta}, \quad (4.7)$$

$$i^* = \alpha \left(\frac{1}{\theta} - \varphi \right), \quad (4.8)$$

where φ is a combined parameter, defined as $\varphi = [\rho + \delta(1-\theta)]/B\theta$. In the steady-state, the growth rate of the economy satisfies the usual optimality condition:

$$g^* = \frac{1}{\theta} (B - \delta - \rho), \quad (4.9)$$

where B is the marginal product of physical capital; and $B - \delta$ is the net marginal product. Because in the steady state, the values of u_t and i_t are constant, c_t , y_t , k_t , h_t and z_t all grow at the same rate, as given by equation (4.9).

Equation (4.9) appears very similar to the equation giving the optimal condition for the steady-state growth rate in a standard neoclassical growth model.⁵⁰ What differentiates the basic Lucas two-sector endogenous growth model from the textbook-style neoclassical growth model is the mechanisms that determine the marginal product of physical capital. Physical capital and labour are the two inputs in the neoclassical growth model, but only physical capital can be accumulated endogenously. Therefore, if no exogenous technological progress occurs, then, as a result of diminishing returns to capital accumulation, the net marginal product of physical capital will eventually fall to the level

⁵⁰ See Blanchard and Fischer (1989, chapter 2) and Barro and Sala-i-Martin (1995, chapter 2) for examples of standard treatments of the neoclassical growth model.

of the subjective discount rate ρ and hence the growth rate eventually falls to zero. The basic Lucas two-sector endogenous growth model has only two essential input factors, physical and human capitals, and both of them can be accumulated.⁵¹ In addition, the model has constant returns to the accumulation of human capital. Therefore, the unbounded increase in human capital induces unlimited physical-capital accumulation and hence long-run growth in per capita output. Indeed, the real returns to physical-capital accumulation depend on the returns to human capital. If the technological parameter in the human capital sector is sufficiently large, i.e., $B > \delta + \rho$, then the steady-state rate of growth is positive.

The steady-state solutions to the basic Lucas model (i.e., equations [4.6]–[4.9]) express the growth and investment rates and the ratio of physical to human capital in terms of technological and taste parameters. As I show in the Appendix I (A), these solutions imply that the steady-state rate of growth can be expressed as a simple linear function of the investment rate:

$$g^* = -\delta + \frac{B}{\alpha} i^*. \quad (4.10)$$

Because $B/\alpha > 0$, the higher the steady-state investment rate, the higher is the steady-state rate of growth. This relation is almost identical to that implied by the one-sector AK model, as both imply that if all the technological parameters are held constant, then the growth rate depends only on the investment rate but not on the ratio of capitals or any

⁵¹ In the Lucas (1988) model, labour is not an essential input factor because labour and human capital are assumed to be perfect substitutes.

other variable. This point has not been well recognized in the growth literature, it thus deserves further elaboration.

It is true that the basic Lucas model allows two different types of capital to accumulate in two different sectors, but because physical capital is used exclusively in the final-goods production sector, the rate of physical-capital investment ultimately determines the growth rate in the steady state; the ratio of the two capitals is not an independent factor in determining the steady-state rate of growth. In fact, a linear association between the ratio of physical to human capital and the investment rate can be expressed as follows:

$$\omega^* = \left(\alpha \frac{A}{B}\right)^{\frac{1}{1-\alpha}} \left(1 - \frac{i^*}{\alpha}\right). \quad (4.11)$$

Equation (4.11) implies that if all the technological parameters are constant, then any change in the investment rate (which can arise from changes in the taste parameters) will lead to a proportional change in the ratio of physical to human capital.

4.2.2. The transitional behaviour of growth and investment rates

The steady state of a model is an equilibrium to which the model converges in the long-run, and the transitional dynamics give the converging processes. In other words, the transitional dynamics of a variable are the time paths along which the variable converges from an initial value to its steady-state value, or moves from one steady state to another. The dynamic behaviour of variables in the Lucas model has been analyzed in the recent growth literature. Through numerical simulations, with a wide range of plausible

parameters, Mulligan and Sala-i-Martin (1993) showed that if an economy has an initial imbalance in the ratio of physical to human capital, ω_0 , then, in the transition, the growth rate of broad output z_t tends to decline monotonically with ω_t . The relationship between the growth rate of the broad output and the ratio of capitals during the transition period is shown in Figure 4.2.

Figure 4.2 The transitional dynamics of growth rate

The curve $g_t = f(\omega_t)$ represents the relationship between g_t and ω_t with all other variables and parameters held constant during the transition period. If an economy starts with $\omega_1 < \omega^*$, then in the transition period, ω_t will increase toward ω^* , while the growth rate g_t will decline toward g^* . If the economy starts with $\omega_2 > \omega^*$, then ω_t will decrease toward ω^* , while g_t will rise toward g^* .

The following transitional relationship between g_t and ω_t can be derived by taking a first-order linear approximation in the neighbourhood of the steady state for the function $g_t = f(\omega_t)$:

$$g_t \approx g^* - \lambda (\omega_t - \omega^*), \quad (4.12)$$

where λ is the slope (which tends to be negative) of the curve in the neighbourhood of the steady state.

Equation (4.12) clearly shows that ω_t plays an important role in determining the rate of growth in a transition period. In fact, the growth rate during the transition, according to this equation, depends on three factors: (1) the steady-state rate of growth, g^* ; (2) the extent to which the economy deviates from the steady state, i.e. $\omega_t - \omega^*$; and (3) the responsiveness of the growth rate to the deviation of ω_t from ω^* , i.e., the slope of the curve in the neighbourhood of the steady state, λ .

Similarly, the transitional behaviour of the investment rate can be characterized by the following linear approximation:

$$i_t \approx i^* + \xi (\omega_t - \omega^*), \quad (4.13)$$

where ξ can be either positive, zero or negative, depending on the combination of parameter values.⁵²

The steady state and the transitional dynamics of the model imply a relation among the growth rate, the investment rate and the ratio of physical to human capital. One can derive this relation by substituting g^* and i^* from equations (4.9) and (4.13) into equation (4.12):

⁵² See a detailed discussion on the transitional behaviour of investment rate in the basic Lucas model in Barro and Sala-i-Martin (1995, chapter 5).

$$g_t \approx -\delta + \frac{B}{\alpha} i_t + \left(\lambda - \frac{B}{\alpha} \xi \right) (\omega_t - \omega^*). \quad (4.14)$$

Equation (4.14) determines the growth rate in the transition period, as well as that in the steady state. During the transition period, $\omega_t \neq \omega^*$, the equation therefore describes the transitional relation among the growth rate, the investment rate, and the ratio of capitals. After the economy reaches the steady state, $\omega_t = \omega^*$, the equation (4.14) collapses into equation (4.9), it hence describes only the long-run relationship between the growth rate and the investment rate. That is why in the steady state of the basic Lucas model, ω_t has no impact on the growth rate.

Equation (4.14) shows that the investment rate has a positive effect on the growth rate. The sign of the coefficient for ω_t during the transition period is generally ambiguous. When ξ is negative,⁵³ the sign of the effect of ω_t depends on the relative size of λ , ξ , B and α . But the ambiguity of the sign of the effect of ω_t on g_t during the transition period is not of a particular concern, since our focus is on the long-run effect of ω_t , which, according to equation (4.10), is equal to zero. Equation (4.14) has the advantage of taking into account the transitional dynamics of the model and specifying the role ω_t plays in determining the growth rate. Thus, it provides a basis for time-series tests of the Lucas two-sector model of endogenous growth.

⁵³ According to Barro and Sala-i-Martin (1995, chapter 5), this is the most probable case.

4.3. The Lucas Externality Model

In the Lucas (1988) model, human-capital accumulation has externalities in the production of final goods. The model differs from the basic version, described in the preceding section, only in the production function of final goods, which is given by

$$y_t = A k_t^\alpha (u_t h_t)^{1-\alpha} h_{at}^\gamma, \quad (4.15)$$

where h_{at} is the average level of human capital in the economy at time t ; and h_{at}^γ captures the effects of human capital on the productivity of physical capital. Because each individual's decision on human-capital allocation can have no appreciable effect on h_{at} , the effect of h_{at} on the productivity is external; therefore, individuals take no account of the effect in deciding how to allocate human capital between the two sectors. But in the equilibrium, $h_{at} = h_t$.⁵⁴ Therefore, I make no distinction between h_{at} and h_t hereafter. The parameter γ can be thought of as an index of the externalities.

As shown in the Appendix I (B), with the external effect of the average level of human capital, the per capita consumption, physical-capital stock, and output still grow at a common constant rate in the steady state. But human-capital stock grows at a lower rate than physical-capital stock and other variables, because individuals fail to take into account the external benefit of human-capital accumulation in allocating their time between final-goods production and schooling. Therefore, unlike the basic Lucas model, the Lucas externality model does not make the ratio of physical to human capital constant

⁵⁴ See Lucas (1988, p. 20).

in the steady state. Instead, in the latter model, the steady-state value of ω_t is determined by the following equation:

$$\omega_t = \left(\frac{\alpha A}{b}\right)^{\frac{1}{1-\alpha}} \left(\frac{\theta-1}{\theta} + \frac{1-\alpha}{1-\alpha+\gamma} \Phi\right) h_t^{\frac{\gamma}{1-\alpha}}, \quad (4.16)$$

where $b = B [1 + \gamma / (1 - \alpha)] + \gamma \delta$ and $\Phi = [\delta (1 - \theta + \gamma) + \rho] / B \theta$. In the steady state, all technological and taste parameters are constant, but the average level of human capital is generally not. If the average level of human capital increases at a rate of $B (1 - u)$, then ω_t will increase as well, with the rate of increase equal to $B (1 - u) \gamma / (1 - \alpha)$.

Although according to equation (4.16), ω_t is not stationary in the long run, a properly re-defined ratio of the two capitals, adjusted for the externalities of human capital, will be stationary. The adjustment implied by equation (4.16) is given by

$$\Omega_t = \omega_t h_t^{-\gamma/(1-\alpha)} = \frac{k_t}{h_t^{1-\gamma/(1-\alpha)}}, \quad (4.17)$$

where Ω_t is the adjusted ratio of physical to human capital. Because the index of externalities, γ , and the share of physical capital, α , are both unobserved, I construct various series of Ω_t with a wide range of plausible values for the parameters γ and α in the empirical estimation below.

The presence of externalities, however, in no way alters the relation of the long-run growth rate to the investment rate and the ratio of physical to human capital. As

shown in Appendix I (B), in the Lucas externality model, the steady-state rate of growth is also a linear function of the investment rate, and it is independent of Ω_t in the long-run, i.e.,

$$g^* = -\delta + \frac{b}{\alpha} i^*. \quad (4.18)$$

Except for the externalities of human capital, the dynamics of the Lucas externality model are similar to those of the basic Lucas model. In particular, Ω_t plays a role in the transition period similar to the role ω_t plays in the model without externalities. Therefore, if one replaces ω_t with Ω_t in equation (4.14), the equation applies equally well to the Lucas externality model.

4.4. The Generalized Lucas Two-Sector Model

Both the basic Lucas model and the Lucas externality model are special cases of two-sector endogenous growth models. One common but unappealing feature of these two models is that the human-capital sector uses no physical capital as a productive input. Rebelo (1991) extended the Lucas model to make human-capital formation employ both types of capital.⁵⁵ Rebelo's generalization of the Lucas two-sector model has the same preference as described by equation (4.1), but the production functions for the two sectors take the Cobb-Douglas form:

⁵⁵ But Rebelo (1991) kept the assumption that human capital has no external effect.

$$y_t = A (v_t k_t)^\alpha (u_t h_t)^{1-\alpha} = c_t + \dot{k}_t + \delta k_t, \quad (4.19)$$

$$\dot{h}_t - \delta h_t = B [(1 - v_t) k_t]^\eta [(1 - u_t) h_t]^{1-\eta}, \quad (4.20)$$

where v_t is the fraction of physical capital used in the production of final goods; and η is the share of physical capital in the human-capital sector.

The steady-state rate of growth can be solved for this model, and it can be shown that the investment rate and the ratio of physical to human capital are constant in the steady state. But the relation of the growth rate to the investment rate and the ratio of the two capitals is more complex than that in either the basic Lucas model or the Lucas externality model. It is impossible to express the growth rate as a linear function of the investment rate alone. Although the positive linkage between the investment and growth rates continues to hold in the generalized model, the model may also imply a non-zero, more likely a negative, long-run effect of the ratio of physical to human capital on the rate of growth. For example, under some more restricted assumptions, Rebelo (1991) expressed the growth rate as a nonlinear function of the investment rate and ω_t . In that function, the effect of the investment rate on the growth rate is positive in the steady-state, and the effect of ω_t is negative. The main explanation for this result is that only a fraction of physical capital is used in the production of final goods in the generalized two-sector model, and the fraction of physical capital allocated to the production of final goods depends on the ratio of physical to human capital.

4.5. Summary

This chapter examines three variants of the Lucas two-sector endogenous growth model, derives testable relations among the growth rate, investment rate, and the ratio of physical to human capital, and produces four findings. First, the long-run relation between the growth and investment rates implied by the basic Lucas two-sector model is identical to that implied by the one-sector AK model: both models imply that the steady-state rate of growth is a positive linear function of the investment rate. Second, in contrast to the AK model, the basic Lucas two-sector model implies that the ratio of physical to human capital may vary during transition period and that the ratio plays an important role in the transitional dynamics of the model. Third, the Lucas externality model suggests that the ratio of the two capitals may increase even in the long run, but after the externalities of human capital are appropriately accounted for, the same relation among growth and investment rates and the ratio of physical to human capital as that implied by the basic Lucas model holds. And last, the generalized Lucas two-sector model, such as that of Rebelo (1991), continues to imply that the investment and growth rates are positively linked, but the model may also imply that the ratio of capitals has a negative long-run effect on the rate of growth.

Because the steady-state implications and the transitional dynamics of the generalized Lucas two-sector model have not been completely worked out, in Chapter 5 I base the empirical tests of the two-sector models primarily on the empirical relation derived from the basic version of the model, i.e., equation (4.14), and that from the Lucas

externality model. But I also consider some less restricted specifications to reflect the spirit of the generalized two-sector model, for instance, by allowing the long-run effect of the ratio of physical to human capital to differ from zero.

CHAPTER 5

THE EMPIRICAL EVIDENCE FOR TWO-SECTOR MODELS

5.1. Introduction

From the empirical viewpoint, the one- and two-sector models of endogenous growth differ mainly in the behaviour of the ratio of physical to human capital. This ratio is constant in the one-sector *AK* model but varies in two-sector models.

As shown in Figure 4.1, the ratios of physical to human capital for the G7 countries rose very rapidly during 1965–1987. Indeed, these ratios have been increasing in all OECD countries since 1960.⁵⁶ Three possible explanations can be given for the persistent and sharp increases in the measured ratios of physical to human capital. First, the economies may be in their transition periods. According to the basic Lucas model, the ratio of physical to human capital may either increase or decrease during the transition period, depending on the direction from which the economy approaches its steady state. Second, as suggested in the Lucas externality model, human-capital accumulation may

⁵⁶ This is true if total years of education is used as a measure of human capital. See Table A2.4, in the Appendix II.

have externalities causing physical-capital stock to grow faster than human-capital stock, even in the steady state. Third, measurement errors may occur for human capital, resulting in an underestimation of the increase in human capital and therefore an overstatement of the increase in the ratio of physical to human capital.

The empirical strategies I adopt in this chapter take account of these three possible explanations. The first explanation underlies the emphasis on the analysis of transitional dynamics, using time-series techniques and including the ratio of capitals in the regression model to capture the transitional effects. The second explanation leads to the exploration of the possible impacts of the externalities of human capital on the estimation of the long-run multipliers in the growth regression. The third explanation motivates the use of alternative proxies for human capital.

5.2. The Empirical Procedure for Estimating Two-Sector Models

Equation (4.14) implies that both the investment rate and the ratio of physical to human capital are determinants of the rate of growth. In this two-sector model, deviations of variables from their steady-state values can arise not only from cyclical fluctuations but also from transitional dynamics. To distinguish the long-run effect from the cyclical and transitional effects, I use a natural extension of the procedure I developed for the time-series test of the one-sector AK model. The technical details of the extended procedure are given below.

First, consider a single-time-series regression model. As in the one-sector AK

model, I use a distributed lag model to capture the dynamic nature of the relation among the growth and investment rates and the ratio of the two capitals. The model can be expressed as

$$g_t = a + B_1(L) x_{1t} + B_2(L) x_{2t} + \varepsilon_t, \quad (5.1)$$

where x_{1t} and x_{2t} now denote the investment rate and the ratio of capitals, respectively; and $B_1(L)$ and $B_2(L)$ are two polynomials of order p in lag operator L .

In a two-sector model with transitional dynamics, the error term ε_t in equation (5.1) reflects both the transitional and the cyclical effects in the economy. Since these effects also cause the observed values of the investment rate and the ratio of capitals to deviate from their steady-state values, it is highly possible that ε_t is correlated with x_{1t} and x_{2t} and their lags.

Defining v_t as the residual from a linear projection of ε_t on the current values of both x_{1t} and x_{2t} and their leads and lags, one can get

$$\varepsilon_t = C_1(L) x_{1t-q} + C_2(L) x_{2t-q} + v_t, \quad (5.2)$$

where $C_1(L)$ and $C_2(L)$ are two lag polynomials of order $2 \times q$, similar to that expressed in equation (3.7).⁵⁷

⁵⁷ In general, the length of the lead may differ from that of the lag, and the length of the lead and lag of the two variables may differ as well. But such differences are unessential in this model because q can be chosen to denote the maximum length of the lead and lag of the two variables.

Because the short-run fluctuations and the transitional dynamics in the model affect all three variables g_t , x_{1t} , and x_{2t} , the polynomials $C_1(L)$ and $C_2(L)$ may contain some non-zero coefficients. By construction, the error term v_t is uncorrelated with x_{1t} and x_{2t} and their leads and lags.

The transitional and cyclical effects cause the dependent and independent variables to deviate from their steady-state values temporally but not permanently, therefore, equation (5.2) represents only a short-run relation. Thus, the long-run multipliers $C_1(I)$ and $C_2(I)$ are both equal to zero, and equation (5.2) can be re-written as

$$\begin{aligned} \varepsilon_t &= C_1(1) x_{1t} + C_1'(L) \Delta x_{1t-p} + C_2(1) x_{2t} + C_2'(L) \Delta x_{2t-p} + v_t \\ &= C_1'(L) \Delta x_{1t-p} + C_2'(L) \Delta x_{2t-p} + v_t. \end{aligned} \quad (5.3)$$

Re-writing equation (5.1) to isolate the long-run effect of x_{1t} and x_{2t} substituting for ε_t from equation (5.3) in equation (5.1), and rearranging it, one gets

$$g_t = a + B_1(1) x_{1t} + D_1'(L) \Delta x_{1t-p} + B_2(1) x_{2t} + D_2'(L) \Delta x_{2t-p} + v_t, \quad (5.4)$$

where $D_j'(L) = C_j'(L)$ for $p > 0$ (i.e., for leads of Δx_{jt}); $D_j'(L) = B_j'(L) + C_j'(L)$ for $p \leq 0$ (i.e., for the current and lagged values of Δx_{jt}); and $j = 1, 2$. Since v_t is by construction uncorrelated with x_{1t} and x_{2t} , an OLS regression of equation (5.4) yields consistent estimates of the long-run multipliers of the investment rate and the ratio of physical to human capital.

Each version of the two-sector model considered in Chapter 4 implies that the investment rate exerts a positive long-run effect on the growth rate, i.e., $B_1(I) > 0$.

However, these versions differ in their prediction of the long-run effect of the ratio of physical to human capital. The basic Lucas model and Lucas externality model suggest that the ratio affects the growth rate only during the transition period, but not in the steady state, i.e., $B_2(I) = 0$. But the generalized version of the model implies that the ratio may also have a negative long-run effect on the growth rate, i.e., $B_2(I) < 0$. Therefore, I estimate equation (5.4) both with and without the restriction of $B_2(I) = 0$.

Because the available annual time series for the ratio of physical to human capital is much shorter than those of growth and investment rates, it is impossible to estimate (5.4) for individual countries. Thus, I estimate the model using pooled time-series data for OECD countries. To this end, I re-write equation (5.4) as a pooled-time-series regression model:

$$g_t^i = \alpha^i + B_1^i(1) x_{1t}^i + B_2^i(1) x_{2t}^i + D_1^{i'}(L) \Delta x_{1t,p}^i + D_2^{i'}(L) \Delta x_{2t,p}^i + v_t^i, \quad (5.5)$$

where the superscript i identifies an individual country or a group of countries in the panel of OECD countries.

5.3. Problems in Human-Capital Measurement

Economists have used various measures of human capital in recent empirical economic growth studies. These measures include adult literacy rates (Romer 1989), secondary-school-enrollment rates (Barro 1991; Mankiw et al. 1992), output of the education sector (Jorgenson and Fraumeni 1992), educational attainment (Barro and Lee

1996), the stock of education (Nehru et al. 1995), Achievement Test Scores (Lee and Lee 1996), labour-income-based human-capital indices (Mulligan and Sala-i-Martin 1995b), and education-based human-capital indices (Mulligan and Sala-i-Martin 1995a; Dinopoulos and Thompson 1997a, b). Of these measures, the educational attainment of Barro and Lee's (1996) study and the stock of education constructed by Nehru et al. (1995) are by far the most comprehensive and widely used.⁵⁸ They are both measured by the average number of schooling years of the working-age population. However, a limitation of using years of schooling as proxy for human capital is that it may inadequately represent human-capital stock because human capital is a much broader concept than years of schooling; for example, human capital may depend on factors such as on-the-job training, experience, health and physical strength, in addition to years of formal schooling.⁵⁹

To see the range of variation in the existing estimates of human capital, I compare the estimates of human capital for the United States during 1960–1990 from four recent major studies, i.e., Mulligan and Sala-i-Martin (1995a, b), Nehru et al. (1995), and Barro and Lee (1996). These estimates are either education-based or labour-income-based. As shown in Table 5.1, the results of this comparison are surprising: the estimated average annual growth rate of human-capital stock in the United States during 1960–1990 varied from as low as 0.29% (measured by the total years of education constructed by Nehru et al.'s [1995]) to as high as 2.36% (measured by the labour-income-based human-capital

⁵⁸ See Pritchett (1996), for example.

⁵⁹ See Behrman and Rosenzeig (1994) and Mulligan and Sala-i-Martin (1995a).

indices of Mulligan and Sala-i-Martin's [1995b] study).

Table 5.1 Alternative human-capital measures for the United States, 1960–1990

Human-capital measures	Levels of human capital per worker		Average annual growth rate (%)
	1960	1990	
(1) Nehru et al. (1995): total years of education per worker ^a	10.73	11.62	0.29
(2) Mulligan and Sala-i-Martin (1995a): education-based human-capital index	0.91	1.00	0.33
(3) Mulligan and Sala-i-Martin (1995a): years of schooling per worker	10.59	13.14	0.72
(4) Barro and Lee (1996): total education attainment per worker	8.66	12.00	1.09
(5) Barro and Lee (1996): secondary and higher education attainment per worker	3.40	6.22	2.01
(6) Nehru et al. (1995): years of secondary and higher education years per worker ^a	2.42	4.43	2.24
(7) Mulligan and Sala-i-Martin (1995b): Labour-income-based human-capital index	39.88	80.88	2.36

Note: ^a Average over 1960–1987.

The tests of the two-sector model require annual time-series data on human-capital stock. To take account of the wide differences in the estimates of human capital, it would be ideal to use more than one measure of human capital in the test. Unfortunately, only one data set, that of Nehru et al. (1995), provides annual time-series data for most OECD countries. The other types of proxies for human capital are available either only for individual countries (e.g., Mulligan and Sala-i-Martin [1995a, b] human-capital indices for

the United States), or for every five years (e.g., Barro and Lee's [1996] data on educational attainment). Because constructing a new human-capital time-series for all OECD countries would be an enormous undertaking, clearly beyond the scope of this study, I use only the human-capital measures from the Nehru et al. (1995) data set.

Nehru et al.'s data on education stocks (i.e., the average number of schooling years of working-age population) are available at three levels: primary, secondary and higher education. Using these data, I construct two proxies for human-capital stocks for OECD countries. One is the total years of education, which is the summation of all three levels; the other is the years of secondary and higher education, excluding primary education. Although the total years of schooling seems to be an appealing indicator of human-capital stock, I also consider the years of secondary and higher education as an alternative indicator of human capital. I do this for the following reasons. First, in the developed economies, primary education alone arguably does not create highly marketable human capital;⁶⁰ thus, years of secondary and higher education are a more appropriate proxy for human capital than total years of education. Second, this alternative indicator relates more closely to secondary-education indicators frequently used in the recent empirical growth literature, such as the enrollment rate in secondary schools.⁶¹ Third, deficiencies appear in the estimates of years of primary education in Nehru et al.'s (1995)

⁶⁰ For example, human capital is often thought of as an augmentation of raw labour or as an asset that allows a worker to earn more than the minimum wage. In the developed countries, a worker with only primary education seems to have little chance to make more than a minimum wage.

⁶¹ See Barro (1991) and Mankiw et al. (1992) for examples.

data set. For example, contrary to the findings of other similar studies, including Barro and Lee's (1996) study, Nehru et al.'s estimates of years of primary education show that the average number of years of primary education declined in the OECD countries at an implausible average rate of 0.5% annually during 1960–1987.⁶²

The growth rate of the human-capital stock indicated by years of secondary and higher education is generally much higher than that indicated by total years of education. For instance, as shown in Table 5.1, in the United States, the total years of education provide the lowest estimate of the human-capital growth rate among the seven indicators examined, whereas the years of secondary and higher education result in the second-highest estimate of the human-capital growth rate. Therefore, using both indicators gives an idea of the sensitivity of the estimates to different measures of human capital. In the following tests, human-capital Indicator I (or the first indicator) is the total years of education, and Indicator II (or the second indicator) is the years of secondary and higher education. Table A2.4, in Appendix II, gives the average annual growth rates of human-capital stock measured by these two indicators, as well as the average annual growth rates of the ratios of physical to human capital for OECD countries.

5.4. Panel-Data Tests of Two-Sector Models

To estimate equation (5.5) using the panel of 22 OECD countries during

⁶² See Nehru et al. (1995, table 1, p. 390).

1965–1987,⁶³ I consider four cases, similar to those examined in the estimation of the one-sector model in Section 3.4:

- (1) All the intercepts and the long- and short-run slope coefficients are the same across countries, i.e., $\alpha' = \alpha$, $B_j'(I) = B_j(I)$ and $D_j''(L) = D_j'(L)$, $j = 1, 2$;
- (2) Intercepts and long-run slope coefficients are the same, but short-run slope coefficients differ, i.e., $\alpha' = \alpha$, $B_j'(I) = B_j(I)$ and $D_j''(L) \neq D_j'(L)$;
- (3) Long-run slope coefficients are the same, but intercepts and short-run slope coefficients differ, i.e., $\alpha' \neq \alpha$, $B_j'(I) = B_j(I)$ and $D_j''(L) \neq D_j'(L)$; and
- (4) Intercepts, as well as long- and short-run slope coefficients differ, i.e., $\alpha' \neq \alpha$, $B_j'(I) \neq B_j(I)$ and $D_j''(L) \neq D_j'(L)$.

For each of these four cases, I examine the specifications both with and without the restriction that the long-run effect of the ratio of physical to human capital on growth is zero and use both human-capital Indicators I and II to estimate the specifications.

In the results reported in this chapter, I use the procedure described in Hamilton (1994) to correct the autocorrelation in the disturbance term,⁶⁴ which is simpler than the

⁶³ In the pooled regressions of the one-sector model, I used panel data from 24 OECD countries during 1950–1990. But in the test of two-sector models, I have to drop Luxembourg and New Zealand from the panel because of the lack of the annual education-stock data for these countries in the data set of Nehru et al. (1995). Data on physical- and human-capital stocks are needed in tests of the two-sector, but not one-sector, models. Because in PWT5.6 the physical-capital-stock data are available only from 1965, and the education-stock data are unavailable after 1987, the sample period in the tests of the two-sector models was reduced to 1965–1987.

⁶⁴ See Hamilton (1994, pp. 508–512) for a description and examples of this procedure.

one proposed by Newey–West (1987).⁶⁵ Also, I report the results of only OLS, but not SUR estimators, in this chapter.⁶⁶

Case 1: $\alpha^i = \alpha$, $B_j^i(1) = B_j(1)$ and $D_j^i(L) = D_j'(L)$

This case assumes the equality of intercepts and slope coefficients in all 22 countries in the sample. The OLS results of this basic pooled-time-series regression are reported in Table 5.2. Two main points are especially noteworthy. First, the long-run effect of the investment rate on the growth rate has the predicted positive sign and it is highly significant in the specifications both with and without the restriction on the long-run effect of the ratio of physical to human capital. This evidence supports endogenous growth models. Second, the estimated long-run multipliers of investment rates appear robust to the change in the indicator of human capital. This is evident from the fact that the estimates of $B_j(1)$ remain positive and highly significant and their magnitudes vary with the human-capital measurement within only a small range.

All the regressions in Table 5.2 include four leads and lags of the first-difference terms of the independent variables. To explore the impacts of the change in the number of leads and lags on the estimated long-run multipliers of the investment rate and the ratio of physical to human capital, I allowed the number of leads of the first-difference terms to

⁶⁵ In fact, the two procedures produce very similar t -statistics for the coefficients. For example, the Newey–West t -statistics for Case 1, which are reported in Table A3.6, are very close to the t -statistics shown in Table 5.2.

⁶⁶ This is mainly because that, as is shown in Chapter 3, both OLS and SUR are consistent estimators, and that the estimates of the long-run effects based on SUR are very similar to those based on OLS.

Table 5.2 Results of pooled regressions for 22 OECD countries, two-sector model, 1965–1987, Case 1

Model:				
	$g_t^i = a + B_1(1)x_{1t}^i + B_2(1)x_{2t}^i + \sum_{k=-4}^4 (d_{1k}\Delta x_{1t-k}^i + d_{2k}\Delta x_{2t-k}^i) + v_t^i, \quad i = 1, \dots, 22.$			
	Indicator I		Indicator II	
	Unrestricted	Restricted	Unrestricted	Restricted
a^a	-0.998 (-1.095)	-1.665 (-1.608)	-2.196** (-2.310)	-2.199** (-2.315)
$B_1(1)$	0.162*** (4.607)	0.138*** (3.451)	0.186*** (5.157)	0.184*** (5.303)
$B_2(1)^b$	-0.564*** (-6.248)	—	-0.002 (-0.135)	—
Adjusted R^2	0.511	0.451	0.485	0.487
Standard error of regression	2.184	2.314	2.240	2.237
F -test for the effect of ω^c	6.852***	2.919***	4.978***	5.547***

Notes: ^a All the t -statistics reported in this and other tables in this chapter are corrected for autocorrelation using the procedure described in Hamilton (1994).

^b Here and throughout the paper, the long-run effect of the ratio of physical to human capital is scaled up by a factor of 10^5 .

^c The F -tests in the unrestricted version of the model are tests of the joint hypothesis of $B_2(1) = 0$ and $d_{2k} = 0$, for $k = -4, \dots, 4$; but in the restricted version, $B_2(1)$ is already restricted to 0, so the F -tests are tests of $d_{2k} = 0$ for $k = -4, \dots, 4$.

vary from two to four, and the number of lags to vary from four to eight. The regression results are reported in Tables A3.7 and A3.8. The increase in the number of leads and lags has only a moderate impact on the goodness of fit of the regressions. For example, the

values of adjusted R^2 and the standard error of regressions indicate that the specifications with a larger number of leads and lags of the first-difference terms of the investment rate provide slightly better fit than those with smaller numbers of leads and lags, whereas the Schwarz Bayesian information criterion suggests the opposite.⁶⁷ One important finding emerging from Tables A3.7 and A3.8 is that the changes in the number of leads and lags in the model make very little difference to the estimated long-run multipliers in terms of the sign, magnitude and the levels of significance.

Case 2: $\alpha^i = \alpha$, $B_j^i(1) = B_j(1)$ and $D_j^i(L) \neq D_j'(L)$

As discussed before, OECD countries are arguably heterogeneous. In particular, the short-run coefficients tend to differ across countries. The regression results of the specifications of country-specific-short-run coefficients are reported in Table 5.3. The estimated long-run multipliers of investment rate are significantly positive and relatively stable throughout the changes in the restriction on the long-run effect of the ratio of physical to human capital and in the human-capital indicators. The values of adjusted R^2 and the standard errors of regressions indicate that allowing the short-run effects to vary across countries significantly improves the goodness of fit. This suggests that sizable differences occur in the short-run effects of the investment rates and the ratio of physical to human capitals on the growth rates among OECD countries. The null hypothesis of zero short- and long-run effects of the ratio of physical to human capital was firmly

⁶⁷ It has been suggested that adjusted R^2 fails to discount the loss of degrees of freedom heavily enough (see, for example Amemiya, 1985, pp. 50–51). Therefore, I show the Schwarz Bayesian information criterion as an alternative measure.

rejected by the F -tests in all specifications. This is consistent with the results reported in Tables 5.2.

Table 5.3 Results of pooled regressions for 22 OECD countries, two-sector model, 1965–1987, Case 2

Model: ^a				
$g_t^i = \alpha + B_1(1)x_{1t}^i + B_2(1)x_{2t}^i + \sum_{k=-3}^2 (d_{1k}^i \Delta x_{1t-k}^i + d_{2k}^i \Delta x_{2t-k}^i) + v_t^i, \quad i = 1, \dots, 22.$				
	Indicator I		Indicator II	
	Unrestricted	Restricted	Unrestricted	Restricted
α	-0.955 (-1.232)	-1.287* (-1.698)	-0.025 (-0.027)	0.651 (0.712)
$B_1(1)$	0.105*** (3.425)	0.089*** (3.008)	0.133*** (3.461)	0.079** (2.216)
$B_2(1)$	-0.204** (-2.190)	—	-0.045*** (-3.118)	—
Adjusted R^2	0.764	0.762	0.675	0.666
Standard error of regression	1.494	1.500	1.752	1.776
F -test for the effects of ω ^b	2.922***	2.902***	1.857***	1.790***

Notes: ^a The numbers of leads and lags of the first-difference terms are reduced from four each in the early tests to two and three, respectively, because country-specific short-run coefficients consume a lot of degrees of freedom.

^b The F -tests in the unrestricted version of the model are tests of the joint hypotheses of $B_2(1) = 0$ and $d_{2k}^i = 0$, for $k = -3, \dots, 2$ and $i = 1, \dots, 22$; but in the restricted version, $B_2(1)$ is already restricted to 0, so the F -tests are tests of $d_{2k}^i = 0$, for $k = -3, \dots, 2$ and $i = 1, \dots, 22$.

Case 3: $\alpha^i \neq \alpha$, $B_j^i(1) = B_j(1)$ and $D_j^i(L) \neq D_j'(L)$

As in the testing of the one-sector model, I explore possible differences in intercept terms among three groups of OECD countries at different levels of economic development.⁶⁸ If one arbitrarily make the second group the reference group, then one can find the difference in the intercepts among the three groups from the coefficients of the dummy variables for groups 1 and 3. Results of regressions with group-specific intercepts and country-specific-short-run-slope coefficients are reported in Table 5.4. The evidence for the inter-group differences in the intercepts is ambiguous. On the one hand, the dummy variable for the third group has a non-zero coefficient in two of the four regressions. But the difference occurs with no particular pattern; i.e., the coefficient of the dummy variable for the third group is significantly negative in the unrestricted regression with Indicator I but significantly positive in the restricted regression with Indicator II. On the other hand, in none of the four regressions does the F -test reject the null hypothesis of no inter-group difference in intercepts. Nonetheless, the important point to note is that allowing intercepts to vary across groups makes little difference to the estimates of the long-run coefficients of the investment rate and ratio of physical to human capital. The sign and magnitude of the coefficients are very close to those found in the common-intercept case (i.e., Case 2) reported in Table 5.3.

⁶⁸ Because of the lack of human-capital data, Luxembourg is withdrawn from the second group, and New Zealand is dropped from the third group.

Table 5.4 Results of pooled regressions for 22 OECD countries, two-sector model, 1965–1987, Case 3

	Indicator I		Indicator II	
	Unrestricted	Restricted	Unrestricted	Restricted
α	0.007 (0.007)	-1.636 (-1.615)	0.969 (0.904)	0.905 (0.825)
DM_1	0.208 (0.378)	-0.604 (-1.104)	-0.735* (-1.753)	-0.376 (-0.921)
DM_3	-1.243** (-2.336)	-0.228 (-0.512)	0.205 (0.562)	0.650** (1.939)
$B_1(1)$	0.108*** (3.177)	0.101*** (2.953)	0.097** (2.455)	0.062 (1.612)
$B_2(1)$	-0.376*** (-3.360)	—	-0.043*** (-2.780)	—
Adjusted R^2	0.768	0.760	0.678	0.673
Standard error of regression	1.482	1.505	1.743	1.759
F -test for $\eta^i = \eta^*$	2.028	0.624	1.673	2.555

Notes: * The F -tests are for the joint hypotheses that the intercepts of the first and third groups are not different from that of the second group; i.e., the coefficients of DM_1 and DM_3 are both zero.

Case 4: $\alpha^i \neq \alpha$, $B_j^i(1) \neq B_j(1)$ and $D_j^*(L) \neq D_j'(L)$

I examine the potential differences in the long-run coefficients among the three group of countries in this case. To allow maximum flexibility in the regressions and to maintain a close comparability with the similar case examined in testing the one-sector model in Section 3.4, I test the group-specific-long-run-coefficient model on the basis of

group-specific intercepts and country-specific short-run coefficients.

As shown in Table 5.5, the results of tests on the inter-group differences in long-run multipliers of the investment rate and the ratio of physical to human capital are sensitive to the indicators of human capital used in the regressions. When indicator I is used, no evidence is found for inter-group differences in the long-run coefficients, and the *F*-tests do not reject the joint null hypothesis of common long-run coefficients in either the restricted or the unrestricted regression. But when Indicator II is used, the long-run multiplier of the investment rate in the third group (i.e., the less advanced economies) is significantly smaller than that in the reference group. However, this sensitivity is not found in the estimates of the long-run effect for the first and second groups; no matter which indicator is used, the long-run multipliers of the investment rates in the reference group are significantly positive, and that in the first group does not significantly differ from that in the reference group.

As noted in the previous chapter, the basic Lucas model and the Lucas externality model imply that the ratio of physical to human capital has only a transitional effect, but the generalized Lucas two-sector model suggests that this ratio may have a non-zero long-run effect. Under some restrictions, the generalized model implies a negative long-run effect of the ratio of physical to human capital on the growth rate. The evidence from pooled-time-series regressions for 22 OECD countries is consistent with the prediction of the generalized model, since the estimated long-run effect of the ratio is significantly negative in seven of the eight unrestricted regressions in the four cases discussed, and all the *F*-statistics firmly reject the hypothesis that the ratio of physical to human capital

Table 5.5 Results of pooled regressions for 22 OECD countries, two-sector model, 1965–1987, Case 4

	Indicator I		Indicator II	
	Unrestricted	Restricted	Unrestricted	Restricted
α	-0.353 (-0.251)	-2.234* (-1.713)	-1.409 (-0.993)	-1.628 (-1.057)
DM_1	-0.507 (-0.202)	1.463 (0.586)	1.752 (0.797)	0.264 (0.131)
DM_3	0.284 (0.113)	1.201 (0.608)	1.509*** (5.634)	1.384*** (5.180)
$B_1(1)$	0.134*** (3.021)	0.123*** (2.725)	0.205*** (3.990)	0.152*** (2.794)
$B_1(I)*DM_1$	0.018 (0.156)	-0.034 (-0.304)	-0.182 (-1.632)	-0.008 (-0.097)
$B_1(I)*DM_3$	-0.085 (-1.064)	-0.057 (-0.738)	-0.058*** (-6.127)	-0.051*** (-5.026)
$B_2(I)$	-0.455*** (-3.216)	—	-0.070*** (-4.726)	—
$B_2(I)*DM_1$	0.122 (0.462)	—	0.161** (2.226)	—
$B_2(I)*DM_3$	0.186 (0.410)	—	-0.009 (-0.150)	—
Adjusted R^2	0.762	0.757	0.710	0.696
Standard error of regression	1.500	1.515	1.654	1.696
F -test for $B_j'(I) = B_j(I)$ *	0.231	0.122	4.529***	5.850***

Notes: * The F -tests are for the joint hypotheses that the long-run multipliers of investment rate and, in the unrestricted cases, the ratio of physical to human capital of the first and third groups do not significantly differ from those of the second group.

has no effect on the growth rate. However, this evidence may not be as conclusive as it appears. Two other possible explanations can be given for the non-zero long-run coefficient of the ratio found in the regressions. First, the economies may have a long transition period and the short time series available may not allow the empirical procedure to completely account for the transitional effect of the ratio, causing the transitional effect to show up in the long-run coefficients.⁶⁹ Second, the possible externalities associated with human capital may have impacts on the estimates of the long-run multipliers of the ratio of physical to human capital. With these externalities, the ratio may shift in the long-run thus distort the estimates of its long-run multipliers. This issue is discussed below.

5.5. Estimating the Model with Externalities of Human Capital

Externalities of human capital may influence the estimates of the long-run growth effect of the investment rate and the ratio of physical to human capital. I explored this

⁶⁹ This problem may occur for two possible reasons. One is that the empirical procedure used in the tests does not include long enough leads and lags of the first-difference terms of independent variables. For example, in equation (5.3), I assume that the relation between the disturbance term and the independent variables holds only in short run; so, $C_1(1)$ and $C_2(1)$ are both zero. If the transition period is long, but only a few leads and lags of the first-difference terms are included in the regression, then $C_1(1)$ and (or) $C_2(1)$ may be non-zero, and the non-zero value of $C_2(1)$ will lead to a non-zero estimate of $B_2(1)$. The other is that the transition period is longer than the sample period. To explore the first possibility, I examined the sensitivity of the estimated long-run multipliers to changes in number of leads and lags included in the regressions in Case 1. I found that the estimated long-run multipliers are very robust to variations in the numbers of leads and lags (see Tables A3.7 and A3.8 in Appendix III). However, if the problem arise due to the second reason, it will not be solved by adding more leads and lags of the first-difference terms in the regressions.

possibility by adjusting the measure of the ratio of physical to human capital to account for the externalities. But because the externalities are unobserved, I made the adjustment by assuming a plausible range of values for the parameters indicating the externalities and tested the sensitivity of the estimates to the change in the parameter values.

According to equation (4.17), the adjustment of the ratio of physical to human capital depends on two key parameters: the share of human capital in the production function, $1 - \alpha$ (where α is the share of physical capital), and the index of externalities, γ . In a production function with both physical and human capitals, α is often assumed to be less than or equal to 0.5.⁷⁰ On the other hand, it is reasonable to assume that the index of externalities of human capital are lower than the share of human capital in the production function of final goods; i.e., γ can be assumed to range from 0 to $1 - \alpha$.⁷¹

Table 5.6 reports the estimation results of the common-intercept-and-slope-coefficient model in which the ratio of the two capitals is adjusted by making γ vary from 0 to 0.5 and assuming that α is equal to 0.5.⁷² I again report the estimation results with

⁷⁰ Barro and Sala-i-Martin (1995, chapter 5) assumed that α equals 0.4–0.5 in their benchmark simulation model; Mankiw et al. (1992) set α equal to 1/3. Using a neoclassical growth accounting framework, with capital and labour but no human capital, Dougherty (1991) estimated that α ranged from 0.38 to 0.45 in the G7 countries during 1960–1990.

⁷¹ As shown in equation (4.15), the total effects (including externalities) of human capital on the production of final goods is $h^{1-\alpha+\gamma}$, and the externalities are measured as h^γ . If $\gamma > 1 - \alpha$, then the externalities would be implausibly greater than the effects that are internalized in the model.

⁷² I also applied the same adjustment to regressions with variable intercepts and variable short-run coefficients; the results differ very little from those of the regressions with unadjusted ratio of physical to human capitals.

Table 5.6 The sensitivity of the estimates to the index of externalities of human capital, 22 OECD countries, 1965–1987 ^a

Model:

$$g_t^i = a + B_1(1) x_{1t}^i + B_2(1) X_{2t}^i + \sum_{k=4}^4 (d_{1k} \Delta x_{1t-k}^i + d_{2k} \Delta X_{2t-k}^i) + v_t^i, \text{ where } X_t^i = x_t^i \cdot (h_t^i)^{-\gamma/(1-\alpha)}$$

	$\gamma = 0$	$\gamma = 0.1$	$\gamma = 0.3$	$\gamma = 0.5$
<i>Indicator I</i>				
$B_1(1)$	0.162*** (4.607)	0.164*** (4.687)	0.167*** (4.751)	0.166*** (4.653)
$B_2(1)$	-0.564*** (-6.248)	-0.811*** (-6.046)	-1.613*** (-4.663)	-2.914*** (-3.820)
Adjusted R^2	0.511	0.509	0.502	0.492
Standard error of regression	2.184	2.189	2.203	2.226
<i>Indicator II</i>				
$B_1(1)$	0.186*** (5.157)	0.188*** (5.192)	0.187*** (5.118)	0.183*** (4.948)
$B_2(1)$	-0.002 (-0.135)	0.014 (0.571)	0.042 (1.527)	0.066** (2.173)
Adjusted R^2	0.485	0.481	0.473	0.467
Standard error of regression	2.240	2.250	2.266	2.280

Note: ^a α is assumed to be equal to 0.5.

two indicators of human capital. Table 5.6 shows that the estimated long-run multipliers of the ratio of physical to human capital are highly sensitive to variations in the measurement of human capital and in the index of externalities of human capital. When the Indicator I of human capital is used, the estimates of $B_2(1)$, the long-run multiplier of the ratio of capitals, are negative and highly significant. But when the Indicator II is used, the estimates of $B_2(1)$ are either zero or significantly positive. However, the estimates of $B_1(1)$ are very robust to the variations in the value of γ . With either human-capital indicator, the magnitudes of the estimated long-run multipliers of investment rate are very stable across a wide range of values for γ . This suggests that the index of externalities of human capital may have very little impact on the estimates of the long-run growth effect of the investment rate.

5.6. The Predictive Power of Two-Sector Models

How well does two-sector endogenous growth models predict the growth rates in the OECD countries as compared to the one-sector AK model? Although the adjusted R^2 and the standard error of regressions are useful quantitative measures of the overall goodness of fit, or the predictive power, they offer no indication of how the pooled regressions fit the data on each individual country. A graphic analysis can provide more information about the predictive performance of the models, particularly for the individual countries.

Figure 5.1 plots the scattergrams of the residuals from the pooled OLS regressions based on specifications of common intercept and long-run coefficient and country-specific short-run coefficients (i.e. Case 2 in both one- and two-sector models). In the one-sector model, all the short- and long-run coefficients of the ratio of physical to human capital are restricted to be zero, whereas in the two-sector model, no restriction on this ratio is imposed. The scattergrams show the overall performance of the one- and two-sector models. While the residuals from the one-sector model scatter broadly with a large number of outliers, those from the two-sector model, using human capital Indicator I, concentrate in a much narrower band, suggesting that the two-sector model has a substantially higher predictive power than the one-sector model.⁷³ Moreover, the residuals from the two-sector model spread evenly in the neighbourhood of zero throughout the sample period in most countries, signifying that although the model makes the long-run growth effects of the investment rates equal across countries, it still provides a good prediction of the growth rate for each country.

⁷³ The scattergram of the residuals from the two-sector model using human capital Indicator II is very similar to that using Indicator I (see Figure A3.2).

Figure 5.1 Residuals of pooled regressions for 22 OECD countries:
the one- and two-sector models.

Note: The residuals from both the one- and two-sector models are based on the OLS regressions with country-specific-short-run coefficients, reported in Tables 3.6 and 5.3.

Figure 5.2 gives more detailed information about how well the pooled regressions with country-specific-short-run-coefficients predict the growth rates in the three largest OECD countries, i.e., the United States, Japan, and Germany. Part (A), on the left panel, shows the predictions of the one-sector AK model: it systematically overpredicts the growth rate in the United States but underpredicts that in Japan; in Germany, the model underpredicts the growth rate in the first half of the sample period (before 1978) and overpredicts it in the second half. This type of systematic prediction error suggests that specification errors occur in the one-sector model. Part (B), on the right panel, plots the predictions of the two-sector model. It tells quite a different story. The predicted growth rates track the observed ones very closely in all three countries, without a persistent prediction error in any of them. The sharp difference in the predictive power of the two models clearly suggests that the ratio of physical to human capital plays an indispensable role in growth regression.

Figure 5.2 Predictions of pooled regressions for the three largest OECD economies: the one- and two-sector models

(A) The one-sector model

(B) The two-sector model

Note: The observed growth rates are shown as solid lines; the predicted growth rates, as dotted lines. The predicted growth rates in the one- and two-sector models are based on the OLS regressions with country-specific-short-run coefficients, reported in Tables 3.6 and 5.3, respectively.

5.7. Summary

In this chapter, the empirical procedure developed in Chapter 3 is extended and applied to tests of two-sector endogenous growth models, using pooled time-series data for 22 OECD countries during 1965–1987. To assess the sensitivity of the estimates to measurement of human capital, the two-sector models are estimated using two indicators of human capital, one based on total years of education and the other on years of secondary and higher education. Both indicators are derived from Nehru et al.'s (1995) data on education stocks.

Four cases are considered in testing the two-sector models, each corresponding to a set of restrictions on intercepts and slope coefficients. In each case, I estimate the models both with and without the restriction on the long-run multiplier of the ratio of physical to human capital. The restricted specification closely reflects the basic Lucas model, but the unrestricted one captures the spirit of the generalized Lucas two-sector model. Using either human-capital indicator, the estimated long-run multipliers of the investment rates are significantly positive and robust to changes in restrictions on intercepts and slope coefficients and to the adjustments in the ratio of physical to human capital for possible externalities of human capital. The long-run effect of the ratio of physical to human capital is negative and significant in a majority of the regressions examined. Although it is unclear whether the negative effect of the ratio of the two capitals arises because of the long transitional effects or the externalities associated with

human capital, it is obvious that the ratio increases significantly the predictive power of the models. Therefore, the ratio of physical to human capital is an indispensable component of growth regression.

CHAPTER 6

CONCLUSION

Neoclassical growth models imply that the investment rate exerts no effect on the long-run rate of growth. But many endogenous growth models suggest that the investment rate and growth rate are positively linked. Therefore, a test of endogenous growth models can take the form of a test of the hypothesis that the long-run effect of the investment rate on the rate of growth is positive.

This study makes two main contributions to the empirical testing of endogenous growth theory. First, this study draws on recent techniques in time-series analysis literature to develop an empirical procedure for estimating the long-run effect of investment rate on the rate of growth, using time-series and panel data. This procedure accounts for the correlation between independent variables and disturbance terms arising from cyclical shocks and transitional dynamics in the economy and thus yields consistent estimates of long-run multipliers. Second, it derives testable relations between growth and investment rates from the Lucas two-sector model. In particular, it shows that the simple linear long-run relationship between growth and investment rates found in the one-sector *AK* model continued to hold in the two-sector models with transitional dynamics. The

relationship derived from the Lucas model, both with and without externalities of human capital, indicates that in the long-run the rate of growth depends only on the rate of investment, but in the transition period it also depends on the ratio of physical to human capital.

The main conclusion of this study is that the investment rate has a significantly positive long-run effect on the rate of growth in OECD countries. This is supported by results from the tests of both the one-sector *AK* model and the two-sector models.

For the *AK* model, the main results of the tests are (1) Individual-country time-series regressions for 24 OECD countries during 1950–1990, using Penn World Table (Mark 5.6) data, produced considerable evidence for a positive long-run effect of the investment rate on the rate of growth. The estimated long-run multiplier of investment rate was found significantly positive in 12 of the 24 OECD countries in the sample, and significantly negative in none. (2) The time-series test using Maddison data on growth and investment rates during 1870–1987 for six main OECD countries revealed that the investment rate has a significant, positive long-run effect on the growth rate in four of these six countries. This result greatly strengthens the results of the individual-country time-series regression. (3) The estimation using pooled-time-series for 24 OECD countries from 1950 to 1990 produces additional evidence for the long-run effect of the investment rate on the rate of growth. The estimated long-run coefficients are significantly positive in all four cases, with various restrictions on the intercept and short- and long-run coefficients, and with both OLS and SUR estimators.

The results from tests of the two-sector models provides further support for

endogenous growth theory. Using pooled-time-series data for 22 OECD countries from 1965 to 1987, this study showed that the investment rate had a positive long-run effect on the rate of growth. These results are robust to alternative measures of human capital, to changes in restrictions on the intercepts and slope coefficients in the regressions, and to variations based on the adjustments in ratio of physical to human capital for possible externalities of human capital. The tests also show that the ratio of physical to human capital significantly raises the predictive power of the model. This suggests that the ratio of physical to human capital plays an indispensable role in growth regression.

This study focused on tests of the endogenous growth hypothesis implied by the *AK* model and the Lucas two-sector endogenous growth model. However, a similar hypothesis may be implied by other types of endogenous growth models. For example, Dinopoulos and Thompson (1997a) showed that an augmented version of the Romer (1990) model implies that investment rates in both physical and human capitals have a positive effect on the growth rate. Hence, the results of this study may support a wide variety of endogenous growth models.

While this study shows that the time-series data for OECD countries are consistent with the predictions of the *AK*-type of endogenous growth models with transitional dynamics, some recent studies using the cross-country-regression approach have shown that the similar data sets also support Solow-type of exogenous growth models with slow convergence. An interesting future research topic is to develop a test that can distinguish an endogenous growth model with long transition and an exogenous growth model with slow convergence, using the same time-series technique and data set.

APPENDIX I. SOLUTIONS OF TWO-SECTOR MODELS

A. The Basic Lucas Model

The Hamiltonian expression for the basic Lucas model, shown as equations (4.1)–(4.4), is given by

$$J = \frac{c_t^{1-\theta} - 1}{1-\theta} e^{-\rho t} + v [A k_t^\alpha (u h_t)^{1-\alpha} - c_t - \delta k_t] + \mu [B(1-u) - \delta h_t], \quad (\text{A4.1})$$

where v and μ are shadow prices of final goods and human capital, respectively; c_t and u_t are control variables; and k_t and h_t are state variables. For simplicity, I suppress the subscript t hereafter.

Defining $\omega = k/h$, and $\chi = c/k$, the growth rates of k , h and ω can be given as

$$g_k = A u^{1-\alpha} \omega^{-(1-\alpha)} - \chi - \delta, \quad (\text{A4.2})$$

$$g_h = B(1-u) - \delta, \quad (\text{A4.3})$$

$$g_\omega = A u^{1-\alpha} \omega^{-(1-\alpha)} - \chi - B(1-u). \quad (\text{A4.4})$$

The first-order conditions, $\partial J/\partial c = 0$ and $\partial J/\partial u = 0$, result in

$$c^{-\theta} e^{-\rho t} = v, \quad (\text{A4.5})$$

$$\frac{\mu}{v} = \frac{A}{B} (1-\alpha) u^{-\alpha} \omega^{\alpha}. \quad (\text{A4.6})$$

The condition $dv/dt = -\partial J/\partial v$ implies

$$\frac{\dot{v}}{v} = -A \alpha u^{1-\alpha} \omega^{-(1-\alpha)} + \delta. \quad (\text{A4.7})$$

The condition $d\mu/dt = -\partial J/\partial \mu$ implies

$$\frac{\dot{\mu}}{\mu} = -\frac{v}{\mu} A (1-\alpha) u^{1-\alpha} \omega^{\alpha} - B (1-u) + \delta. \quad (\text{A4.8})$$

By substituting for v/μ from equation (A4.6) to equation (A4.8), one gets

$$\frac{\dot{\mu}}{\mu} = B - \delta. \quad (\text{A4.9})$$

Differentiating equation (A4.5) with respect to time, dividing the left-hand side of the differentiated equation by $c(t)^{-\theta} e^{-\rho t}$ and the right-hand side by v , and substituting for the rate of change of v from (A4.7), one gets

$$g_{\epsilon} = \frac{1}{\theta} (\alpha A u^{1-\alpha} \omega^{-(1-\alpha)} - \delta - \rho). \quad (\text{A4.10})$$

The growth rate of χ can be determined by using equations (A4.10) and (A4.2):

$$g_{\chi} = \frac{\alpha - \theta}{\theta} A u^{1-\alpha} \omega^{-(1-\alpha)} + \chi - \frac{1}{\theta} [\delta(1 - \theta) - \rho]. \quad (\text{A4.11})$$

Differentiates equation (A4.6) with respect to time and substituting for the rate of change of ν and μ from equations (A4.7) and (A4.9) respectively, one gets

$$g_u = B \frac{1 - \alpha}{\alpha} + Bu - \chi. \quad (\text{A4.12})$$

Equations (A4.4), (A4.11) and (A4.12) form a differential equation system. In the steady state, the growth rates of ω , u , and χ are all equal to 0, and the steady-state values of three variables can be given by

$$\omega^* = \left(\alpha \frac{A}{B} \right)^{\frac{1}{1-\alpha}} \left[\varphi + \frac{(\theta - 1)}{\theta} \right], \quad (\text{A4.13})$$

$$u^* = \varphi + \frac{\theta - 1}{\theta}, \quad (\text{A4.14})$$

$$\chi^* = B \left(\varphi + \frac{1}{\alpha} - \frac{1}{\theta} \right), \quad (\text{A4.15})$$

where φ is a combined parameter defined as $\varphi = [\rho + \delta(1 - \theta)]/B\theta$.

Defining the investment rate as the proportion of final goods not consumed, i.e.,

$$i \equiv 1 - \frac{c}{y}, \quad (\text{A4.16})$$

one obtains the following relation between i and χ :

$$i = 1 - \chi \frac{k}{y}, \quad (\text{A4.17})$$

where k/y is the inverse of the average product of physical capital, which is, according to equations (A4.13) and (A4.14), a constant, i.e.,

$$\frac{y}{k} = A u^{1-\alpha} \omega^{-(1-\alpha)} = \frac{B}{\alpha}. \quad (\text{A4.18})$$

Equations (A4.15) and (A4.18) imply

$$i^* = \alpha \left(\frac{1}{\theta} - \varphi \right). \quad (\text{A4.19})$$

Equations (A4.13), (A4.14) and (A4.19) are given in the text as equations (4.6)–(4.8).

By substituting for ω and u from equations (A4.13) and (A4.14) to (A4.10), one gets the steady-state rate of growth of per capita consumption:

$$g^* = \frac{1}{\theta} (B - \delta - \rho). \quad (\text{A4.20})$$

This equation is shown as equation (4.9) in the text. Because in the steady state, variables

y , k , and h grow at the same rate as c , equation (A4.20) also gives the growth rate of k , h , y and z .

The relation between the growth rate of physical capital and the investment rate can be derived from equations (A4.2), (A4.17) and (A4.18), as

$$g_k = -\delta + \frac{B}{\alpha} i. \quad (\text{A4.21})$$

Because in the steady state, the growth rate of physical capital is equal to the growth rates of consumption, output and human capital, equation (A4.21) can be rewritten simply as

$$g^* = -\delta + \frac{B}{\alpha} i^*. \quad (\text{A4.22})$$

This equation appears as equation (4.10) in the text in Chapter 4.

Equations (A4.13) and (A4.19) imply a steady-state relation between i and ω

$$\omega^* = \left(\alpha \frac{A}{B}\right)^{\frac{1}{1-\alpha}} \left(1 - \frac{i^*}{\alpha}\right). \quad (\text{A4.23})$$

This is the equation (4.11) in the text.

B. The Lucas Externalities Model

The Lucas (1988) model with externalities differs from the basic Lucas model only in allowing the production function in final goods sector to have externalities of the

average level of human capital. The Hamiltonian expression of the model is

$$J = \frac{c_t^{1-\theta} - 1}{1-\theta} e^{-\rho t} + \nu [A k_t^\alpha (u h_t)^{1-\alpha} h_t^\gamma - c_t - \delta k_t] + \mu [B(1-u) - \delta h_t], \quad (\text{B4.1})$$

The growth rates of k , h and ω can be given as

$$g_k = A u^{1-\alpha} \omega^{-(1-\alpha)} h_t^\gamma - \chi - \delta, \quad (\text{B4.2})$$

$$g_h = B(1-u) - \delta, \quad (\text{B4.3})$$

$$g_\omega = A u^{1-\alpha} \omega^{-(1-\alpha)} h_t^\gamma - \chi - B(1-u). \quad (\text{B4.4})$$

Following the same procedure as the one used to solve the optimization problem of equation (A4.1), one gets

$$g_\chi = \frac{\alpha-\theta}{\theta} A u^{1-\alpha} \omega^{-(1-\alpha)} h_t^\gamma + \chi - \frac{1}{\theta} [\delta(1-\theta) - \rho]; \quad (\text{B4.5})$$

$$g_u = \frac{B}{\alpha} [1 + \frac{\gamma u}{1-\alpha} - (\alpha-\gamma)(1-u)] - \chi - \frac{\gamma \delta}{\alpha}; \quad (\text{B4.6})$$

$$g_\omega = \frac{\gamma}{1-\alpha} B(1-u). \quad (\text{B4.7})$$

In the steady state, the growth rates of u and χ are equal to 0, and the steady-state

values of two variables can be given by

$$u^* = \frac{1-\alpha}{1-\alpha+\gamma} \Phi + \frac{\theta-1}{\theta}, \quad (\text{B4.8})$$

$$\chi^* = B \left[\Phi + \left(\frac{1}{\alpha} - \frac{1}{\theta} \right) \frac{1-\alpha+\gamma}{1-\alpha} \right] + \frac{\gamma \delta}{\alpha}, \quad (\text{B4.9})$$

where Φ is a combined parameter defined as $\Phi = [\rho + \delta(1-\theta+\gamma)]/B\theta$.

Equations (B4.4) and (B4.7) imply that the average product of physical capital is given by

$$A u^{1-\alpha} \omega^{-(1-\alpha)} h_c^\gamma = \frac{b}{\alpha}, \quad (\text{B4.10})$$

and the growth rate of per capita consumption satisfies the usual optimal condition as

$$g^* = \frac{1}{\theta} (b - \delta - \rho), \quad (\text{B4.11})$$

where b , defined as $b = B [1 + \gamma / (1 - \alpha)] + \gamma \delta$, is the marginal product of physical capital in the steady state.

Substituting for u in equation (B4.10) from (B4.8) and re-arranging (B4.10), one can get the value of ω in the steady state:

$$\omega = \left(\frac{\alpha A}{b} \right)^{\frac{1}{1-\alpha}} \left(\frac{\theta-1}{\theta} + \frac{1-\alpha}{1-\alpha+\gamma} \Phi \right) h^{\frac{\gamma}{1-\alpha}}. \quad (\text{B4.12})$$

Equation (B4.12) appears as (4.16) in the text. Because in the steady state, h is not constant, nor is ω . But if one defines $\Omega = \omega h^{-\gamma/(1-\alpha)}$, then Ω will be constant in the steady state, i.e.,

$$\Omega = \left(\frac{\alpha A}{b}\right)^{\frac{1}{1-\alpha}} \left(\frac{\theta-1}{\theta} + \frac{1-\alpha}{1-\alpha+\gamma} \Phi\right). \quad (\text{B4.13})$$

Equations (B4.2), (A4.17) and (B4.10) imply that the growth rate of per capita output, as well as per capita consumption, physical and human capital, is as follows:

$$g^* = -\delta + \frac{b}{\alpha} i^*. \quad (\text{B4.14})$$

This is the equation (4.18) in the text.

APPENDIX II. THE DATA

A. The Sources

(1) *Growth Rate*. Growth rates for 1950–1990 are derived using first difference of natural logarithm of real gross domestic product (GDP) per worker (1985 international prices), i.e., *RGDPW* series, from Summers and Heston's Penn World Table (Mark 5.6). Growth rates during 1870–1987 are constructed from GDP per capita data provided by Jones (1995), which are based on Maddison's (1982, 1989) data, as compiled by Bernard (1991), except for the data on the Canadian per capita GDP growth rate during 1870–1900, which are from Urquhart (1993).

(2) *Investment Rate*. The investment rate is defined as the total gross physical capital formation as a percentage of GDP. The data on the investment rates after 1950 are from the *real investment share of GDP (%)* (1985 international prices), i.e., the *I* series in the Penn World Table (Mark 5.6). The data on the investment rates for Australia, Canada, France, Japan, the United Kingdom and the United States during 1870–1987 are based on Maddison's (1991a) data on the gross domestic fixed investment as a percentage of GDP, including gross domestic non-residential fixed investment and the gross investment in dwellings.

(3) *Physical-Capital Stock*. The data on physical-capital stock during 1950–1990

used in this study are the non-residential capital stock per worker (in 1985 international prices), i.e., *KAPW* series from PWT5.6. They are created using a perpetual-inventory method applied to investment data and an initial assumption about the capital stock.

(4) *Human-Capital Stock*. This study uses Nehru et al.'s (1995) annual educational stock data as proxy for human capital stock. This data set provides average number of schooling years of working-age population during 1960–1987 for 22 of the 24 OECD countries in the sample, excluding Luxembourg and New Zealand.

The data used in the tests of *AK* model in this study differ from those in Jones' (1995) study in several ways. The main differences are summarized in Table A2.1.

Table A2.1 The data used in the tests of the *AK* model: differences and similarities between Jones' (1995) and this study

Sample	Variables	Jones (1995)	This paper
15 selected OECD countries, ^a since 1950	Growth rate	Calculated from real GDP per worker in 1985, international prices, 1950–1988, from Penn World Table (Mark 5) (PWT5) of Summers and Heston (1991)	Calculated from real GDP per worker in 1985 international prices, 1950–1990, from Penn World Table (Mark 5.6) (PWT5.6) of Summers and Heston (1991)
	Investment rate	Gross domestic investment as a percentage of GDP in current international prices, 1950–1988, from PWT5	Gross domestic investment as a percentage of GDP in 1985 international price, 1950–1990, from PWT5.6
9 other OECD countries, ^b since 1950	Growth rate	Not included	Calculated from real GDP per worker in 1985 international prices, 1950–1990, from PWT5.6
	Investment rate	Not included	Gross domestic investment as a percentage of GDP in 1985 international prices, 1950–1990, from PWT5.6
6 selected OECD countries, ^c 1870–1987	Growth rate	Derived from real GDP per capita in Maddison (1982, 1989), as compiled and extended by Bernard (1991)	Same as Jones (1995)
	Investment rate	Not included	Gross total domestic fixed investment as % of GDP, from Maddison (1991a)

Note: ^a They are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Sweden, the United Kingdom and the United States.

^b The nine countries are Greece, Iceland, Ireland, Luxembourg, New Zealand, Portugal, Spain, Switzerland, and Turkey.

^c They are Australia, Canada, France, Germany, the United Kingdom and the United States.

The differences in the sources of the data used in this and Jones' (1995) study may explain some of the differences in the results. One of the typical examples of the differences in data is illustrated in Figure A2.1.

Jones (1995) used the *CI* series from PWT5 for investment rates, but this study uses the *I* series from PWT5.6. The time trend of the investment rates in PWT5 for the United States is positive, but that in PWT5.6 is negative.

B. Population Growth Rates and Real GDP Per Worker

Table A2.2 The average population growth rates (%) in 24 OECD countries, 1950–1990

Country	1950–1990	1965–1987
Canada	1.65	1.23
France	0.76	0.61
Germany	0.63	0.24
Italy	0.50	0.46
Japan	0.94	0.96
United Kingdom	0.32	0.23
United States	1.23	1.04
Group Average	0.86	0.68
Australia	1.80	1.63
Austria	0.31	0.21
Belgium	0.36	0.23
Finland	0.55	0.35
Luxembourg	0.67	0.52
Netherlands	0.97	0.83
Norway	0.65	0.54
Sweden	0.51	0.40
Switzerland	0.92	0.53
Group Average	0.75	0.58
Denmark	0.45	0.36
Greece	0.76	0.69
Iceland	1.43	1.12
Ireland	0.42	0.93
New Zealand	1.39	1.05
Portugal	0.40	0.51
Spain	0.81	0.87
Turkey	2.46	2.39
Group Average	1.02	0.99

Source: PWT5.6.

Table A2.3 The real GDP per worker (in 1985 international prices) in 24 OECD countries, 1990

Country	Real GDP per worker in 1990	Rank of real GDP per worker among OECD countries
Australia	30312	9
Austria	26700	15
Belgium	31730	5
Canada	34380	3
Denmark	24971	19
Finland	27350	13
France	30357	8
Germany	29509	10
Greece	17717	22
Iceland	24978	18
Ireland	24058	20
Italy	30797	7
Japan	22624	21
Luxembourg	37903	1
Netherlands	31242	6
New Zealand	25413	17
Norway	29248	11
Portugal	16637	23
Spain	26364	16
Sweden	28389	12
Switzerland	32812	4
Turkey	8632	24
United Kingdom	26755	14
United States	36771	2

Note: The real GDP per worker in 1990 is measured in 1985 international prices.

Source: PWT5.6.

C. Human Capital Indicators and the Ratios of Physical to Human Capital

Table A2.4 The average annual growth rates (%) of physical- and human-capital stocks per worker and ratios of capitals in 22 OECD countries, 1960–1987

Country	Physical capital	Human capital		Ratio of capitals	
		Indicator I	Indicator II	Indicator I	Indicator II
Australia	2.48	1.10	3.17	1.38	-0.69
Austria	6.21	-0.02	5.48	6.23	0.72
Belgium	3.61	0.41	4.51	3.19	-0.90
Canada	3.19	0.67	3.34	2.52	-0.16
Denmark	3.60	0.66	4.26	2.93	-0.66
Finland	4.00	1.54	4.89	2.46	-0.89
France	4.46	0.40	5.30	4.06	-0.84
Germany	5.40	-0.07	3.46	5.47	1.94
Greece	5.67	1.06	3.51	4.61	2.16
Iceland	3.79	1.49	4.93	2.30	-1.14
Ireland	5.09	-1.04	3.55	6.13	1.54
Italy	4.02	0.93	4.91	3.09	-0.89
Japan	8.04	0.31	2.00	7.72	6.03
Netherlands	3.28	0.24	3.64	3.04	-0.36
Norway	0.90	0.47	5.52	0.43	-4.62
Portugal	4.77	2.15	5.44	2.62	-0.67
Spain	6.18	1.24	6.89	4.94	-0.71
Sweden	3.50	0.52	5.04	2.98	-1.54
Switzerland	3.50	0.15	4.26	3.35	-0.75
Turkey	5.17	3.12	5.89	2.04	-0.73
United Kingdom	3.41	0.37	1.74	3.04	1.67
United States	2.72	0.39	2.30	2.33	0.42

Source: PWT5.6 and Nehru et al. (1995).

APPENDIX III. ADDITIONAL TESTING RESULTS

Table A3.1 Long-run effect of investment rate on growth rate in 24 OECD countries, with five leads and lags of the first difference of investment rates, 1950–1990

Model:			
$g_t = a + B(1)x_t + \sum_{k=-5}^5 d_k \Delta x_{t-k} + v_t$			
Country	Long-run effect $B(1)$	Adjusted R^2	Durbin–Watson statistics
<i>Selected 15 countries</i>			
Australia	0.264 (1.416)	0.757	1.728
Austria	-0.183 (-1.281)	0.681	1.572
Belgium	0.662*** (3.979)	0.722	1.246
Canada	-0.354 (-0.983)	0.578	1.214
Denmark	-0.076 (-1.521)	0.862	1.709
Finland	0.226 (1.527)	0.616	1.113
France	0.089 (0.734)	0.676	1.043
Germany	0.498*** (7.118)	0.898	0.956
Italy	0.569*** (8.131)	0.879	1.107

Table A3.1 (continued)

Country	Long-run Effect $B(1)$	Adjusted R^2	Durbin–Watson statistics
Japan	0.018 (0.198)	0.670	1.486
Netherlands	0.529*** (5.566)	0.824	1.885
Norway	-0.180 (-1.071)	-0.156	1.820
Sweden	0.189** (2.095)	0.756	2.064
United Kingdom	0.140 (1.001)	0.741	1.321
United States	0.959* (1.862)	0.736	2.111
<i>Nine other OECD countries</i>			
Greece ^a	0.375*** (4.608)	0.538	2.113
Iceland	0.092 (0.486)	0.444	1.466
Ireland	0.255*** (3.001)	0.652	1.984
Luxembourg	0.105 (1.399)	0.589	1.568
New Zealand	1.101*** (2.764)	0.399	2.358
Portugal ^b	0.182 (0.819)	0.232	1.156
Spain	0.244** (2.584)	0.653	0.879
Switzerland	-0.068 (-0.349)	0.649	1.524
Turkey	-0.058 (-0.176)	-0.012	1.883

Note: ^a 1950–1991.^b 1950–1990.

Table A3.2 Long-run effect of the investment rate on the growth rate in six major developed countries, 1870–1987, with a dummy variable for World War I and II and the Great Depression ^a

Model:				
$g_t = a + B(1)x_t + B(1)WD \cdot x_t + \sum_{k=4}^4 (1+WD)d_k \Delta x_{t-k} + v_t$				
Country	$B(1)$	$B(1) \cdot WD$	Adjusted R^2	Durbin–Watson statistics
Australia	0.144* (1.928)	-0.473* (-1.710)	0.070	2.382
Canada	0.091 (0.443)	-0.261 (-0.734)	0.108	1.422
France	0.295*** (6.482)	-0.276 (-0.177)	0.472	2.354
Japan ^b	0.206** (2.585)	-0.779 (-0.826)	0.540	2.261
United Kingdom	0.097 (1.316)	1.306*** (2.765)	0.280	1.984
United States	-0.273 (-0.429)	-1.485 (-1.664)	0.623	1.676

Note: ^a A dummy variable, WD , is used for 1910–1950 to control for the impacts of the World Wars I and II and the Great Depression on the estimates of long-run effects.

^b 1885–1987.

Table A3.3 Pooled regressions for 24 OECD countries, using a common intercept and long-run coefficient model with various number of lags of the change in investment rate

	4 lags	6 lags	8 lags
<i>Common short-run coefficient</i>			
<i>a</i>	-0.408 (-0.556)	-0.106 (-0.148)	0.297 (0.419)
<i>B</i> (1)	0.121*** (4.372)	0.108*** (3.987)	0.092*** (3.417)
Adjusted <i>R</i> ²	0.434	0.446	0.460
Standard error of regression	2.392	2.268	2.337
<i>Country-specific short-run coefficient</i>			
<i>a</i>	-0.585 (-0.867)	-0.119 (-0.194)	0.346 (0.636)
<i>B</i> (1)	0.124*** (4.846)	0.103*** (4.457)	0.084*** (4.068)
Adjusted <i>R</i> ²	0.499	0.535	0.581
Standard error of regression	2.252	2.169	2.060
<i>F</i> -statistics for common short-run coefficients	1.440***	1.538***	1.678***

Note: ^a Each regression includes four leads of the first difference of the investment rate.

^b The sample period, 1960–1988, is set according to the specification with the largest numbers of leads and lags, i.e., four leads and eight lags.

Table A3.4 Results of pooled regressions for 24 OECD countries, using country-specific-intercepts and short-run-slope-coefficients models, 1965–1987 ^a

	Common long-run coefficient	Group-specific long-run coefficients
$B(1)_1$ ^b	0.196*** (5.621)	0.225*** (3.414)
$B(1)_2$	—	0.181*** (3.672)
$B(1)_3$	—	0.181*** (2.925)
Adjusted R^2	0.560	0.559
Standard error of regression	2.214	2.127
F-statistics for common intercept	5.988***	—
F-statistics for common long-run coefficients ^c	—	0.220

Note: ^a These results are comparable to the OLS results in Tables 3.7 and 3.8 in the text.

^b In the case of common-long-run-coefficients model, $B(1)_1$ stands for the common long-run coefficient for the three groups

^c F -test of the common-long-run coefficient versus group-specific-long-run coefficients is done on the basis of the country-specific-intercepts and short-run-slope-coefficients model.

Table A3.5 Results of pooled regressions for 22 OECD countries, one-sector model, 1965–1987 ^{a, b}

	Common-short-run coefficients	County-specific-short-run coefficients
α	-2.138** (-2.413)	-3.703*** (-4.794)
$B(1)$	0.177*** (5.393)	0.229*** (8.219)
Adjusted R^2	0.421	0.497
Standard error of regression	2.376	2.215
F -test for common- short-run coefficients	—	1.255**

Note: ^a The panel of 22 of the 24 OECD countries, excluding Luxembourg and New Zealand, for 1965–1987, was chosen based on the availability of human-capital-stock data, and it is used in tests of two-sector models.

^b The results are comparable to the OLS estimates in Tables 3.5 and 3.6 in the text.

Table A3.6 Results of pooled regressions for 22 OECD countries, two-sector model, 1965–1987, Case 1, Newey–West *t*-statistics

Model:				
	$g_t^i = \alpha + B_1(1)x_{1t}^i + B_2(1)x_{2t}^i + \sum_{k=4}^4 (d_{1k}\Delta x_{1t-k}^i + d_{2k}\Delta x_{2t-k}^i) + v_t^i$			
	Indicator I		Indicator II	
	Unrestricted	Restricted	Unrestricted	Restricted
α	-0.998 (-1.162)	-1.665* (-1.917)	-2.196** (-2.554)	-2.199** (-2.567)
$B_1(1)$	0.162*** (5.097)	0.138*** (4.037)	0.186*** (5.942)	0.184*** (6.027)
$B_2(1)$	-0.564*** (-5.443)	—	-0.002 (-0.129)	—
Adjusted R^2	0.511	0.451	0.485	0.487
Standard error of regression	2.184	2.314	2.240	2.237

Table A3.7 The sensitivity of the estimated long-run multipliers of the investment rate and the ratio of capitals to changes in the number of leads and lags, with human-capital Indicator I

	4 lags	6 lags	8 lags
<i>Regressions with 2 leads</i>			
α	-0.006 (-0.659)	-0.009 (-0.944)	-0.007 (-0.742)
$B_1(1)$	0.104*** 2.742	0.118*** (3.064)	0.104*** (2.615)
$B_2(1)$	-0.355*** (-3.530)	-0.417*** (-3.881)	-0.327*** (-2.730)
Adjusted R^2	0.458	0.462	0.464
Standard error of regression	2.125	2.112	2.114
Schwarz information criterion	-7.390	-7.324	-7.256
<i>Regressions with 4 leads</i>			
α	-0.005 (-0.445)	-0.007 (-0.679)	-0.004 (-0.358)
$B_1(1)$	0.088** (2.058)	0.100** (2.287)	0.076* (1.674)
$B_2(1)$	-0.336*** (-3.195)	-0.394*** (-3.503)	-0.286** (-2.269)
Adjusted R^2	0.456	0.459	0.462
Standard error of regression	2.129	2.122	2.117
Schwarz information criterion	-7.313	-7.247	-7.180

Note: The sample period, 1973 –1983, is set according to the specification with the largest numbers of leads and lags for all regressions in this table.

Table A3.8 The sensitivity of the estimated long-run multipliers of investment rate and the ratio of capitals to changes in the number of leads and lags, with human-capital Indicator II

	4 lags	6 lags	8 lags
<i>Regressions with 2 leads</i>			
α	-0.016 (-0.659)	-0.018* (-1.779)	-0.014 (-1.442)
$B_1(1)$	0.137*** (3.614)	0.142*** (3.728)	0.124*** (3.254)
$B_2(1)$	-0.017 (-0.710)	-0.020 (-0.778)	-0.007 (-0.279)
Adjusted R^2	0.428	0.427	0.440
Standard error of regression	2.182	2.184	2.159
Schwarz information criterion	-7.336	-7.262	-7.213
<i>Regressions with 4 leads</i>			
α	-0.017* (-1.735)	-0.017* (-1.705)	-0.012 (-1.225)
$B_1(1)$	0.109*** (2.696)	0.113*** (2.684)	0.085** (2.019)
$B_2(1)$	0.067 (1.644)	0.057 (1.263)	0.075* (1.654)
Adjusted R^2	0.437	0.431	0.447
Standard error of regression	2.166	2.177	2.147
Schwarz information criterion	-7.279	-7.196	-7.152

Note: See the note in Table A3.7.

Figure A3.1 The five-year moving average of the investment and growth rates in six major developed countries, 1870–1987

Notes: The five-year moving averages of the investment rates are plotted as solid lines on the left scale, and those of the growth rates of per capita GDP are shown as dashed lines on the right scale.

Figure A3.2. Residuals of pooled regressions for 22 OECD countries, the two-sector model, using human-capital Indicator I and II

Note: The residuals of the regressions with both human-capital indicators are based on the country-specific-short-run coefficient specification, and the sample period is 1968-1985. The main results of the two-sector model are reported in Table 5.3.

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