Technological Change, Diffusion and Output Growth

Maurizio Baussola

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Summary

The thesis presents a critical review of both traditional and new growth models emphasising their main implications and points of controversy. Three main research directions have been followed, refining hypothesis advanced in the sixties. We first find models which follow the learning by doing hypothesis and therefore consider knowledge embodied in physical capital. The second class of models incorporate knowledge within human capital while the third approach considers knowledge as generated by the research sector which sells designs to the manufacturing sector producing capital goods. A typical outcome of such models is the existence of externalities which causes divergence between market and socially optimal equilibria. Policy intervention aimed at subsidising either human capital or physical capital is thus justified.

Empirical analysis has received new impetus from the theoretical debate. However, past empirical tests are mainly based on heterogeneous cross section data which take into account mean growth rates over given periods of time, and ignore pure time series analysis. On empirical grounds, the role of investment in the growth process has been emphasised. This variable has also been decomposed to consider the impact of machinery and equipment investment alone.

In this thesis we have underlined six aspects of endogenous growth models, which in our opinion reflect the main points of controversy:

i) scale effects;
ii) the treatment of knowledge as a production input;
iii) the role of institutions;
iv) the empirical controversy dealing with the robustness of growth regression estimates and the measurement of the impact of some crucial variables (e.g., investment) on growth;
v) the simplified representation of R&D;
vi) the absence of any discussion of diffusion phenomena.

We then propose a new version of an R&D endogenous growth model, which explicitly incorporates the diffusion of innovations and permits comparison with results derived from other models which do not consider the diffusion process. In this new model the interaction between the sector producing final output and the sector producing capital goods generates the time path of diffusion and hence the growth rate of the economy.

In this new model there is a clear growth effect of a change in the interest rate. Such a change, on the one hand, affects the determination of the value of human capital in research, and, on the other hand, affects the diffusion path of new producer durables. This is important for policy because policy aimed at stimulating growth may be mainly concerned with reductions of the interest rate and will thus cause a higher allocation to human capital in research and a larger supply (and use) of new intermediate goods.

In addition, there is another clear growth effect which derives from changes in the parameter which defines the diffusion path of new capital goods. An increase in the value of this parameter again causes an increase in human capital devoted to research and an upward shift of the diffusion path, thus increasing the long-run growth rate. This result underlines the difference with previous R&D endogenous growth models in that we now have a clear distinction between the sectors producing and using new capital goods.

The empirical implications of the theoretical models are then investigated by testing the causal link between R&D and investment, on the one hand, and output growth and investment on the other hand. Indeed, a crucial task of any empirical investigation dealing with endogenous growth theories is to explain the nature of the links between industrial research, investment and economic growth. There is much room for study in this framework, as there are still only a few studies analysing these relationships. Our analysis deals with both aggregate data for the US and UK economies and an intersectoral analysis for the US manufacturing sector. We have used a test procedure which allows us to analyse both the short-run and the long-run properties of the variables using cointegration techniques. We are able to test for any feedback between these variables, thus giving more detailed and robust evidence on the forces underlying the growth process.

The results suggests that R&D Granger causes investment in machinery and equipment only in the US economy. However, there is evidence of long-run feed-back implying that investment may also affect R&D. In the UK economy there is no evidence for R&D causing investment nor is there strong evidence of long-run feed-back between the two variables. This suggests that the causal link between R&D and investment may not be thought of as a stylised fact in industrialised economies.

We have also analysed the relationship between investment and output growth to test whether investment may be considered as the key factor in the growth process. We find little support for the hypothesis that investment has a long-run effect on growth. In addition, causality tests support bi-directional causality between these variables in the US economy while in the UK economy, output growth causes investment both in the short-run and in the long-run.

CHAPTER I

1. Introduction

Growth theory has been a central issue in Economics since classical economists. In the 1950s and 1960s it became the most important issue in economics following seminal studies by Schumpeter (1934) and Solow (1956). Solow's neo-classical approach contributed to resolving controversial results from previous models (Harrod, (1939, 1949) and Domar (1946)). Studies by Koopmans (1968) and Cass (1965) refined the standard neo-classical approach with a more detailed theoretical framework, while the studies by Kuznets (1955) contributed to the empirical debate on economic growth.

After this period of controversial debate, interest in growth related issues decreased, due to both theoretical and empirical problems. The main drawback of the neo-classical model lies in the assumption that technological change is exogenous and as a result the model cannot discriminate between the different variables which cause long-run growth. This analytical drawback contributed to a decrease in interest, both theoretical and empirical, in economic growth until the first half of the 1980s, when new models were proposed building on the seminal work by Arrow (1962), which endogenised technical progress through a learning-by-doing approach.

Within this framework, the work by Romer (1986) represents the starting point for the new debate, which focuses on the variables which may cause long-run growth.

Knowledge becomes the crucial element in the innovative process with the new growth theory considering its role incorporated in either physical or human capital. This new analytical approach refines the neo-classical model and the studies by Arrow (1962) and Uzawa (1965). Some of the new models also consider knowledge as the result of the specific activity of an R&D sector in the economy. In such models technological progress is endogenised through the production function of the R&D sector., the parameters of which determine, therefore, the long-run growth rate of the economy. A typical outcome of such models is an externality associated with knowledge, as it is not a fully excludable good. Thus, the market equilibrium may diverge from the welfare optimum, depending on the nature of the knowledge generating process. Such externalities may affect either human or physical capital but in all cases the outcome is a remuneration of human capital or physical capital which is less than is socially optimal.

Despite recent analytical improvements there is still a gap between theoretical predictions and empirical findings. The empirical results (which are typically based on new data sets for the world economies (Penn World Table)) often contrast with the conclusions of the theoretical models and, in general, there has been no improvement in the explanatory capacity of these models compared with the traditional neo-classical model. This fact is crucial, as it may reduce future interest in growth theory and hence in the explanation of the determinants of long-run growth.

Together with the new interest in growth issues, there has also been a growing interest in the economics of innovation. Building upon the work by Schumpeter (1939), during the 1980s and 1990s there has been a growing body of theoretical and empirical research on innovation issues.

However, there is still a wide gap between the analysis of new growth theory, which endogenises the innovation process, and the economics of technological change. In particular we think that the analysis of the diffusion process in the innovation field may be used to help understand the possible impact of innovation on output fluctuations within the analytical structure of endogenous growth models. Hence, in this thesis, we have incorporated an explicit treatment of the diffusion of innovation into an aggregate endogenous growth model. Both theoretically and empirically, we have then analysed in depth the implications for the aggregate model, focusing on the causal links between the key variables within the model, i.e., R&D, investment and output growth.

The thesis is organised as follows. In the second chapter we critically review both traditional and new growth models. We focus particularly on the R&D endogenous growth models (Romer 1990a, 1990b, Grossman and Helpman 1991a, 1991b) which represent the theoretical framework used later to incorporate the diffusion process into an aggregate growth model. We also analyse the empirical evidence relating to such models.

The third chapter analyses the theory of technological diffusion, focusing on both traditional demand-based models and integrated models, incorporating both demand and supply sectors. We focus on such integrated models as they represent the analytical framework used to incorporate diffusion in an aggregate growth model (presented in the fourth chapter).

In the fourth chapter, we present a new version of an R&D endogenous growth model, which explicitly incorporates the diffusion of innovations and permits comparison with results derived from original models which do not consider the diffusion process.

The last three chapters present empirical results. This are mainly concerned with tests of the main predictions of endogenous growth models, i.e., the causal link between R&D and investment, on the one hand, and output growth and investment on the other hand.

This analysis sheds light on relationships which are still controversial within the empirical debate and may help in our understanding of the empirical implications of the growth models analysed in the previous chapters. The analysis deals with both aggregate data for the US and UK economies and an intersectoral analysis for the US manufacturing sector. Jointly these give a detailed picture of the characteristics of the relationship between investment, R&D and growth.

CHAPTER II

2. Technological Change and Endogenous Growth

2.1 Introduction

The determinants of economic growth have always been a point of controversy in economic debate. In this chapter we shall analyse the main theoretical and empirical studies which have significantly contributed to the debate on economic growth and focus on the research lines representing the benchmark for the analyses described in the following chapters.

In the initial stages the theoretical debate concentrated mainly on the use of an aggregate production function to represent the economy and the growth rate was taken as exogenous, given an exogenous growth rate of the population and technical progress. Debate on these issues, which ceased for roughly twenty years, received further impetus from a new theoretical perspective which tends to focus on the variables endogenously determining the growth rate, and may therefore explain the long-run differences between different economies. A starting point for this debate is provided by Romer's analysis (1986), in which the growth rate is endogenously determined following a learning-by-doing approach (Arrow 1962). Since then new models have been developed, concentrating in particular on the role of knowledge incorporated either in physical capital, as in the original Arrow model, or in human capital (Uzawa 1965, Lucas 1988). In addition, technical progress may be endogenised considering a third approach providing a specific sector of the economy (Research and Development) which produces knowledge which may then be used to produce new capital goods.

These new elements of the debate will be analysed, with particular emphasis on their implications. It will be useful, however, to start this analysis with a brief review of the traditional models, and then move on to analyse the new approaches in greater detail.

2.2 An Overview of Traditional Growth Models

2.2.1 Harrod-Domar

We shall start the analysis of the traditional approaches with the Harrod-Domar model[1]. We can summarise the model briefly as follows:

$$(2.1) \quad L^s = L_0 e^{nt}$$
$$(2.2) \quad I = S$$
$$(2.3) \quad S = sY$$
$$(2.4) \quad I = v\left(\frac{dY}{dt}\right)$$

[1] See Harrod (1939) and Domar (1946).

Equation [2.1] represents the labour supply. It is assumed that the labour force grows at an exogenous and constant rate equal to n, while [2.2] represents the equilibrium conditions on the goods market. Savings [2.3] are a constant proportion of the national income (Y). Equation [2.4] implies that, along a growth path where the goods market is in equilibrium, expectations are always fulfilled: in other words, at any time t, firms will invest as long as the equilibrium between the desired and effective capital stock is reached. Recall that v represents the desired capital/output ratio and dy/dt the expected change in income. Along a balanced growth path, the expected and effective growth rates coincide.

In this context, without technical progress, the output growth rate coincides with the growth rate of the labour force (n):

$$(2.5) \quad Y = \frac{1}{\eta} L_0 e^{nt}$$

$$(2.6) \quad \therefore \quad \frac{\dot{Y}}{Y} = n$$

where $\dot{Y} = \frac{dY}{dt}$ and η is the labour-output ratio. Technical progress may be introduced assuming that it is neutral, labour augmenting and growing at a constant rate [2].

We therefore have

[2] Recall that the neutrality of technical progress referes to three different concepts:
a) neutrality according to Hicks; b) neutrality according to Harrod and c) neutrality according to Solow.

$$(2.7) \quad \eta = \eta_0 e^{g_a t}$$

where g_a is the growth rate of technical progress. Equation [2.7] establishes that the labour-output ratio decreases (due to technical progress) following an exponential path determined by the parameter g_a. Output dynamics is therefore determined by the parameters n and g_a:

$$(2.8) \quad Y = \frac{1}{h_0} L_0 e^{(g_a + n)t}$$

We therefore have

$$(2.9) \quad \frac{\dot{Y}}{Y} = g_a + n$$

Equation [2.9] shows the natural growth rate when technical progress is included in the model. From [2.3] and [2.4] we get the definition of the warranted growth rate which maintains the goods market equilibrium. Thus we have

$$(2.10) \quad v \frac{dY}{dt} = sY$$

And therefore

$$(2.11) \quad \frac{1}{y}\frac{dy}{dt} = \frac{s}{v}$$

Equation [2.11] implies

$$(2.12) \quad Y = Y_0 e^{(\frac{s}{v})t}$$

The warranted growth rate is s/v. Therefore, a balanced growth path is only reached when $s/v = n + g_a$, i.e., when both per-capita income and per capita-capital stock grow at the exogenous rate g_a, which is determined by technical progress, and full employment is guaranteed. However, s and v are not endogenous variables and, therefore, there is no guarantee that the equality between the natural and warranted growth rates is reached in the economy.

The solution of this dilemma in the Harrod-Domar model has been twofold. On the one hand, the post-Keynesian school has emphasised the endogenity of the saving propensity considering its diversification among the social classes (Pasinetti 1962, 1974). On the other hand, the neo-classical approach (Solow 1956) has used the definition of aggregate production function to enodogenise the capital-output ratio.

2.2.2 The Neo-Classical Model

In the neo-classic model there is complete price and wage flexibility thus allowing market clearing conditions at each point in time. Furthermore, the use of production inputs varies according to the technology represented by the aggregate production function and, therefore, the capital-output ratio may vary as well thus modifying the assumption of the Harrod-Domar model in which the capital-output ratio is fixed.

The economy may be represented by means of an aggregate production function of the type

$$(2.13) \quad Y = f(K(t), A(t)L(t))$$

where K represents the aggregate capital stock, L the labour force and A a variable which incorporates the change in labour productivity. It is assumed that A is an increasing and monotonic function of time. Equation [2.13] may be written in terms of output per efficient labour units

$$(2.14) \quad y = f(k) \equiv f(k,1)$$
$$f'(k) > 0; f''(k) \leq 0$$

$$\text{where} \qquad y = \frac{Y}{AL}; \; k = \frac{K}{AL}$$

It is also assumed that labour productivity grows at a constant rate g_a and the growth rate of the labour force is n. This means that [3]

$$(2.15) \quad A(t) = e^{g_a t}$$
$$(2.15') \quad L(t) = e^{nt}$$

[3] It is assumed for simplicity that $A_0 = L_0 = 1$.

If the previous hypothesis that each individual saves a constant ratio s of his/her income is maintained, aggregate savings are given by

$$(2.16) \quad S = sY$$

Savings are used to finance investments, and assuming no capital depreciation, we get

$$(2.17) \quad \dot{K} = sALf(k)$$

Combining [2.15], [2.15'] and [2.17], we may write

$$(2.18) \quad \dot{k} = sf(k) - (g_a + n)k$$

This equation is a version of the well-known fundamental equation of the Solow model, which determines the evolution of the capital-labour ratio.

When $sf(k)$ is greater than $(g_a + n)k$, the capital-labour ratio grows, while on the other hand k decreases when $sf(k) < (g_a + n)k$. Figure 1 shows the equilibrium path of the capital-labour ratio, which in steady-state is constant (k^*). Under stationarity conditions, the capital stock and output grow at the same rate $(g_a + n)$, which represents the long-run growth rate of the economy.

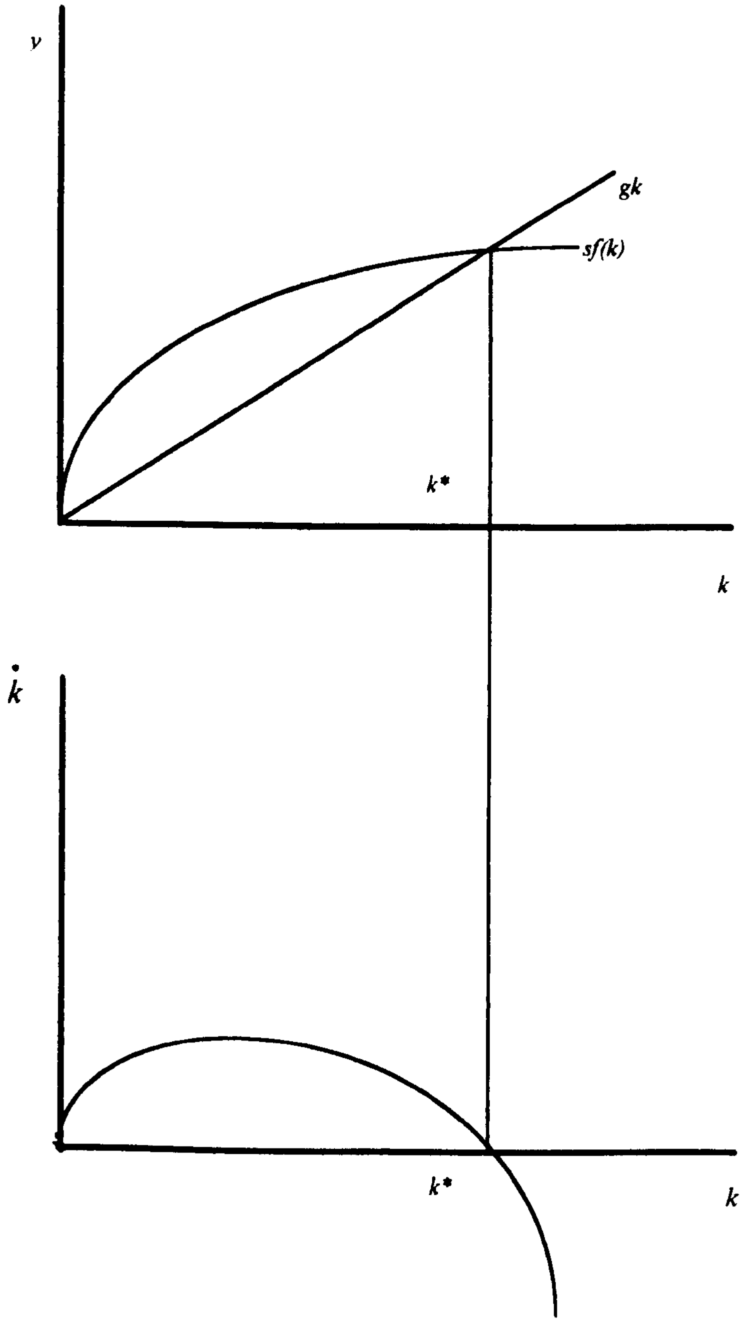

Figure 2.1 *Equilibrium in the Neo-classical model*

2.2.3 Optimal Growth

The traditional neo-classical model may be modified to endogenise savings and to determine the optimal growth rate, which, without external effects and assuming rational expectations, coincides with the competitive market equilibrium. The theoretical framework is a synthesis of the analysis of Ramsey (1928), Cass (1965) and Koopmans (1965).

The representative individual has a utility function of the type

$$(2.19) \quad U(C) = \frac{C_t^{1-\sigma} - 1}{1-\sigma}$$

where C_t is consumption at time t and σ defines the intertemporal elasticity of substitution. The representative consumer chooses the consumption path which maximises the utility function [2.19], under the constraint of the available resources. It is assumed that the aggregate production function is of the type $Y = f(K(t),A(t)L(t))$. This equation may be written in terms of output per efficient labour unit, as in the case of [2.14]. The intertemporal maximisation problem may be formulated as follows:

$$(2.20) \quad Max \int_0^{\infty} e^{-(\rho-n)t} \left(\frac{(ce^{g_a t})^{1-\sigma} - 1}{1-\sigma} \right) dt$$

s.t.

$$\dot{k} = f(k) - c - (g_a + n + \lambda)k$$

where c is consumption per efficient labour unit, ρ is the rate of time preference, n the population growth rate, g_a the productivity growth rate and λ the capital depreciation rate [4].

The corresponding Hamilton conditions of this problem are

$$(2.21)\quad H = e^{-(\rho-n)t}\left(\frac{(ce^{g_a t})^{1-\sigma}-1}{1-\sigma}\right)+m\big(f(k)-c-(g_a+n+\lambda)k\big)$$

$$(2.21')\quad H_c = 0 \Leftrightarrow e^{-(\rho-n)t}e^{g_a t}(ce^{g_a t})^{-\sigma}-m=0$$

$$(2.21'')\quad H_k = -\dot{m} \Leftrightarrow -m(f'(k)-(g_a+n+\lambda))$$

$$(2.21''')\quad \lim_{t\to\infty} m(t)=0; \lim_{t\to\infty} H = 0$$

where m is the co-state variable. Taking logarithms of [2.21'], differentiating with respect to time t and combining with [2.21'], we get the growth rate of c:

$$(2.22)\quad \frac{\dot{c}}{c} = \sigma^{-1}(f'(k)-(\sigma g_a+\lambda+\rho))$$

The inclusion of exogenous labour productivity growth enables us to solve the problem of the constancy of per-capita income and consumption in the original neo-classical model.

[4] The function f(k) satisfies the following conditions (Inada conditions): f(0)=0, f'(0)=∞, f'(∞)=0. These conditions are sufficient for a steady-state equilibrium.

In this case, in steady state, the ratio $\bar{c} = \frac{C}{AL}$, i.e., per capita consumption in efficient labour units, is constant. However, per capita consumption in physical units grows at the rate g_a since [2.23] holds:

$$(2.23) \quad \frac{C}{L} = \bar{c}\,A$$

If this result solves the problem of the cap on per capita income and consumption typical of the neo-classical model without technological change, it does not, however, explain the source of technical progress and therefore the source of economic growth. This contradiction in the original neo-classical model, which, in fact, represents the real objective of a theoretical investigation on growth, has been faced by the later endogenous growth models. This line of research aims at investigating the source of technological change and its impact on growth and on the ability of the market economy to reach efficient growth paths.

2.3 Endogenous Growth Models: the role of knowledge

2.3.1 Learning by Doing

Despite its success, the neo-classic model does not provide an explanation of the source of technical progress and therefore of the main factors which may affect the long-run growth of per capita income.

Endogenous growth models have tried to fill this gap by defining the variables which may affect technical change. However, the theoretical framework of this line of research lies in models refined in the 60s (Arrow 1962, Uzawa 1965, Shell 1966), in which the role of knowledge as production input is considered. There has been three main lines of research which have tried to identify the mechanisms of knowledge accumulation.

Firstly, knowledge has been incorporated in physical capital (Arrow 1962), depending on its accumulated stock. The rationale of this analytical tool is that firms improve and add knowledge (learning-by-doing) to the capital goods they produce. This knowledge incorporated in capital goods may be freely used by other firms, thus contributing to the productivity of production inputs in the whole economy.

Secondly, knowledge has been incorporated in human capital (Uzawa 1965, Lucas 1988). Again there may be an external effect (however, not essential to determine an endogenous growth rate of the economy), deriving from the use of human capital in the production process, which, as in the case of learning-by-doing, creates the typical problem of market equilibrium with externalities.

Finally, there are models (R&D models) which consider knowledge accumulation as the result of an activity specifically dedicated to this purpose (Shell 1966, Romer 1990a, 1990b, Grossman and Helpman 1991). We initially consider the first type of model then discuss the other theoretical approaches.

We shall start by analysing the non-vintage version of the Arrow model, which simplifies the exposition while leaving unchanged the conclusions (Sheshinski 1967). Consider a specification where the aggregate production function is a Cobb-Douglas of the type

$$(2.24)\quad Y = K^{b} A(t) L^{1-b}$$

where $A(t)$ represents the state of knowledge at time t. Following the learning by doing hypothesis, we may write

$$(2.25)\quad Y = K^{\beta} L^{1-\beta} \kappa^{\alpha}$$

where κ represents the state of knowledge, which is a function of accumulated investment. As in the traditional neo-classic model, it is assumed that consumers intertemporaly maximise their utility function. Thus we have

$$(2.26)\quad Max \int_{0}^{\infty} e^{-\rho t} \left(\frac{c^{1-\sigma} - 1}{1-\sigma}\right) dt$$

$$\text{s.v.}\quad \dot{k} = k^{\beta}\kappa^{\alpha} - c$$

From the Hamilton conditions we get

$$(2.27)\quad H = e^{-\rho t}\left(\frac{c^{1-\sigma}}{1-\sigma}\right) + m(k^{\beta}\kappa^{\alpha} - c)$$

$$(2.28')\quad H_{c} = 0 \Leftrightarrow e^{-\rho t} c^{-\sigma} = m$$

$$(2.28'')\quad H_{k} = -\dot{m} \Leftrightarrow \dot{m} = -m(\beta k^{-(1-\beta)} \kappa^{\alpha})$$

$$(2.28''')\quad \lim_{t\to\infty} m(t) = 0; \lim_{t\to\infty} H = 0$$

where κ is the aggregate measure of capital stock, k is per capita-capital stock and L is the labour force.

The equilibrium condition in the capital market requires that $\kappa = Lk$. Taking logarithms of [2.28'], differentiating with respect to time t and finally substituting [2.28"], we get

$$(2.29) \quad \frac{\dot{c}}{c} = \gamma = \sigma^{-1}(\beta k^{-(1-\alpha-\beta)} L^{\alpha} - \rho)$$

This condition states that the consumption growth rate is proportional to the difference between the marginal product of capital and the rate of time preference. In this version of the model it is assumed that the labour force is constant.

It is worth noting that this model shows an endogenous growth rate $\gamma > 0$ provided that $\beta + \alpha = 1$. If we consider a logarithmic transformation of [2.29] and differentiate with respect to time t, we get

$$(2.30) \quad 0 = \beta(\alpha + \beta - 1)\gamma$$

If $\alpha + \beta < 1$, the only steady state growth rate is $\gamma = 0$, as in the traditional neoclassic model without technical progress.

This result suggests that even with increasing returns to scale a positive steady state growth rate is not always attainable. In fact, the value of α must be sufficiently high to satisfy the condition $\beta + \alpha = 1$.

In this case the growth rate would be[5]

$$(2.31)\quad \gamma = \sigma^{-1}(\beta L^{\alpha} - \rho)$$

This growth rate implies a scale effect which derives from the size of the labour force. This effect depends on the assumption that knowledge is incorporated in the aggregate stock of capital. On the other hand, if one assumes that knowledge is proxied by the average capital stock, a growth rate independent from the size of the labour force may be derived[6]

The market and optimal equilibria differ since the social planner would maximise the utility function [2.27], no longer assuming the stock of knowledge (incorporated in the capital stock) as given. The first order conditions are therefore obtained including all capital stock, even that part which is external to the individual firm. The Hamilton conditions become

$$(2.32)\quad H = e^{-\rho t}\left(\frac{c^{1-\sigma}}{1-\sigma}\right) + m(k^{\alpha+\beta}L^{\alpha} - c)$$

$$(2.32')\quad H_c = 0 \Leftrightarrow e^{-\rho t}c^{-\sigma} = m$$

$$(2.32'')\quad H_k = -\dot{m} \Leftrightarrow \dot{m} = -m((\alpha+\beta)k^{-(1-\alpha-\beta)}L^{\alpha})$$

$$(2.32''')\quad \lim_{t\to\infty} m(t) = 0;\ \lim_{t\to\infty} H = 0$$

This implies the following growth rate

[5] Romer (1986) has shown that a technology with increasing return to scale such that $\beta+\alpha>1$ may cause a positive and growing growth rate.

[6] In fact (2.29) becomes: $\gamma=(\beta-\rho)/\sigma$.

$$(2.33)\quad \gamma = \sigma^{-1}\left((\beta + \alpha)\kappa^{-(1-\beta-\alpha)}L^{\alpha} - \rho\right)$$

This growth rate is higher than the market equilibrium growth rate. In other words, the competitive equilibrium implies an underinvestment by the single firm, since it does not internalise the externality represented by the stock of knowledge incorporated in physical capital. This underinvestment therefore causes lower production.

We may link this analytical approach, which incorporates the stock of knowledge in physical capital, to a wider field of investigation, where the so-called learning by watching is taken into account (King and Robson 1989, 1992).

The basic idea in this framework is that there is a demonstration or contagion effect which comes from observations of new ideas embodied in new investment The empirical evidence discussed in Cohen and Levinthal (1989) shows that many innovations in one firm or industry determine development and innovations in other firms and industries. Scott (1989) views investment as the engine of growth, because it brings about new investment opportunities, which may be called learning externalities. In the model proposed in King and Robson, the level of technological knowledge evolves over time following an S shaped profile (truncated logistic) determined by the aggregate net investment rate. The output growth rate is endogenously determined from the conditions for optimum consumption. Assuming a standard isoelastic utility function of the form used in (2.19), it is then possible to solve a system of five equations in five endogenous variables.

Denote G_n as the natural growth rate given by the technical progress function, which is a function of the investment rate (i):

$$(2.34)\quad G_n = f(i)$$

From the intertemporal maximisation problem one can derive the growth rate of consumption[7]

$$(2.35)\quad \frac{\dot{c}}{c} = \frac{(r-\rho)}{\sigma}$$

where ρ is the rate of time preference, r is the interest rate and σ defines the intertemporal elasticity of substitution.

The investment criterion adopted by firms requires that the marginal product of capital be equal to its user cost. Assuming a Cobb Douglas technology, the production function in per capita terms is: $y = A^{1-a}k$, where A represents the stock of knowledge and k per capita capital. It is assumed that the labour force is constant and this allows the normalisation $L = 1$. Knowledge is a function of investment and evolves according to

$$(2.36)\quad A = A_0 e^{f(i)t}$$

The investment criterion condition implies

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[7] Given a utility function of the type $U(c) = C^{1-\sigma}/1-\sigma$, from the intertemporal maximisation of this function one gets: $\frac{\dot{c}}{c} = \frac{(r-\rho)}{\sigma}$

$$(2.37)\quad \frac{\alpha}{v} = \frac{r}{1-t} + \lambda$$

where v is the capital-output ratio, r is the interest rate, λ is capital depreciation and t is the tax rate[8].

Equilibrium requires that [2.34] and [2.35] be equal, i.e., the natural growth rate and the warranted (rational expectation) growth rate must be equal. Furthermore, in equilibrium the investment rate is given by

$$(2.38)\quad i = \frac{\dot{c}}{c} v$$

Solving the system represented by equations [2.35], [2.37] and [2.38], gives the equilibrium growth rate

$$(2.39)\quad \frac{\dot{c}}{c} = \gamma = \frac{i(\rho + \lambda(1-t))}{\alpha(1-t) - \sigma i}$$

It is worth noting that this solution is not unique given the non-linearity of the technical progress function. Equation [2.39] states that the growth rate compatible with

[8] Note that $\alpha/v = MP_k$ since $MP_k = A^{1-a}\alpha k^{a-1}$ and v is the capital output ratio in steady-state. The marginal product of k is therefore: $MP_k = \alpha y/k$.

capital market equilibrium is an increasing and convex function of i. The equilibrium solutions are given by the intersections with the technical change function (Figure 2.2).

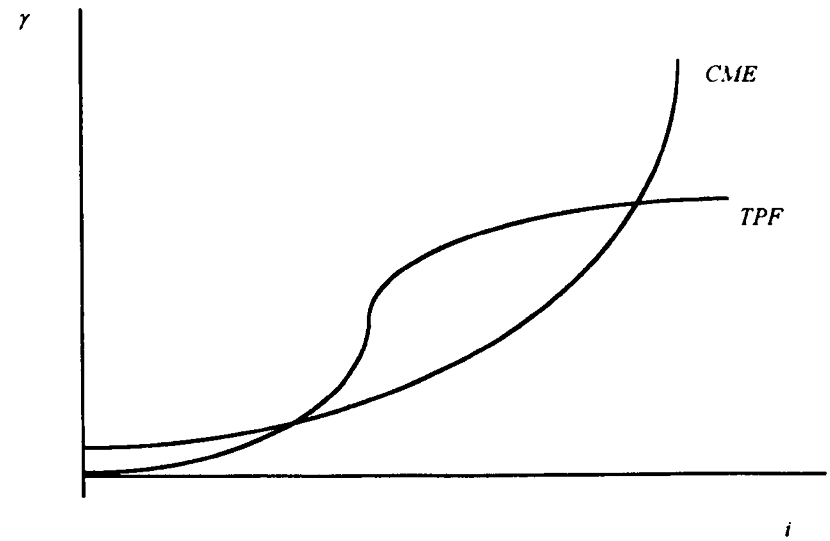

Figure 2.2

CME=Capital market equilibrium

TPF=Technical progress function

2.3.2 Knowledge and Human Capital

The second analytical approach considers knowledge incorporated in human capital. In the model proposed by Uzawa (1965) we again have a labour augmenting technical progress within an aggregate production function with constant returns to scale. The labour input is allocated between the education and production sectors. The aggregate production function is of the type: $Y = f(K, AL)$. The model may be summarised as follows:

$$(2.40) \quad Max \int_0^{\infty} c(t) e^{-\rho t} dt$$

$$(2.40') \quad \dot{k} = sy - \lambda k$$

$$(2.40'') \quad \dot{A} = A\varphi\left(\frac{L_E}{L_P}\right)$$

where c is per capita consumption, A the state of technological knowledge, λ the capital depreciation rate, s the proportion of savings to national income and y per capita income.

In other words, the problem is the usual intertemporal maximisation of consumption subject to the constraint determined by the accumulation of physical capital and technology. The latter is a function of the ratio between the labour force employed in the education sector (L_E) and in production (L_P). It is worth stressing that the division of the labour force into two components has been widely considered in many later endogenous growth. models. It is possible to derive the optimal allocation of the labour force between the production and education sectors and the optimal capital-labour and capital-output ratios from the conditions for intertemporal maximisation. In the model it is shown that the optimal growth rate is reached when the growth rate of labour productivity $\frac{\dot{A}}{A}$ is equal to the growth rate of the capital-labour ratio $\frac{\dot{k}}{k}$.

Following the line of research outlined by Uzawa is the Lucas model (1988), which represents a generalisation of the previous models of human capital accumulation. Consider again a closed economy with competitive markets, identical individuals and a technology with constant returns to scale in absence of externalities. We also define h as a measure of the qualification of each worker. It is assumed that a worker with this qualification level assigns a fraction $q(h)$ of his/her time to productive activity and a fraction $1 - q(h)$ to his/her qualification.

In addition to this direct effect of human capital on productivity, an external effect is considered. This latter refers to the mean level of qualification of human capital, which may also influence the productivity of other inputs and therefore may affect the growth rate of the economy. As in the previous model it is assumed that consumers maximise their utility in an infinite time horizon. We then have

$$(2.41) \quad Max \int_0^\infty \frac{c^{1-\sigma}}{1-\sigma} e^{\rho t} L(t)dt$$

$$(2.41') \quad \dot{K} = AK^{\beta}[qhL]^{1-\beta} \hat{h}^{\vartheta} - Lc$$

$$(2.41'') \quad \dot{h} = \varepsilon h(1-q)$$

It is also assumed that the labour force grows at an exogenous rate n.

The constraint on the *LHS* shows net investment and on the *RHS* national income and aggregate consumption. This specification is obtained assuming that all workers have the same qualification level h and choose the time allocation q. It is also assumed that the technological level is constant and equal to A. The term $\hat{h}^{\vartheta}$ captures the external effect of human capital and is proxied by the mean qualification level of the labour force. The second constraint concerns the accumulation of human capital. This equation implies that the accumulation of human capital is a linear function of the effort dedicated to this accumulation process (1 - q).

If there is no effort in the accumulation of human capital (q = 1), the economy does not accumulate human capital. On the other hand, if q = 0, i.e. the entire effort is dedicated to the accumulation of human capital, the economy grows at the rate ε. The equilibrium condition in the labour market means that $\hat{h}^{\vartheta}=h$.

The conditions which show the growth rate of per capita consumption and human capital can be derived from the Hamilton conditions.

$$(2.42)\quad H=e^{-\rho t}\left(\frac{c^{1-\sigma}}{1-\sigma}\right)L(t)+m\left(AK^{\beta}(qL)^{1-\beta}h^{1-\beta+\vartheta}-Lc\right)+l\left(h\varepsilon(1-q)\right)$$

$$(2.42')\quad H_c=0\Leftrightarrow e^{-\rho t}c^{-\sigma}=m$$

$$(2.42'')H_q=0\Leftrightarrow m\left(AK^{\beta}(1-\beta)(qLh)^{-\beta}Lh^{1+\vartheta}\right)=l(h\varepsilon)$$

$$(2.42''')H_k=-\dot{m}\Leftrightarrow \dot{m}=-m\left(\beta AK^{\beta-1}(qL)^{1-\beta}h^{1-\beta+\vartheta}\right)$$

$$(2.42''')H_h=-\dot{l}\Leftrightarrow \dot{l}=-m\left((1-\beta)AK^{\beta}(qL)^{1-\beta}h^{1-\beta+\vartheta}\right)-l\varepsilon(1-q)$$

From conditions [2.42'] and [2.42"] it is possible to derive the equation which defines the growth rate of per capita consumption γ.

$$(2.43)\quad \frac{\dot{c}}{c} = \gamma = \sigma^{-1}(\beta A K^{\beta-1}(qL)^{1-\beta} h^{1-\beta+\vartheta} - \rho)$$

The accumulation rate of physical capital may be obtained from the constraint [2.41] and from [2.43][9]

$$(2.44)\quad \frac{\dot{K}}{K} = \gamma + n$$

One should consider now the accumulation of human capital $\frac{\dot{h}}{h} = \gamma_h$ From [2.43] we get

$$(2.45)\quad \frac{(\gamma\sigma + \rho)}{\beta A} = K^{\beta-1}(qL)^{1-\beta} h^{1-\beta+\vartheta}$$

Taking logarithms of (2.45) and then differentiating with respect to time yields:

$$(2.46)\quad \frac{\dot{h}}{h} = \frac{\gamma(1-\beta)}{(1-\beta+\vartheta)}$$

---

[9] Equation (2.44) is derived considering that: $\frac{\dot{K}}{K} = AK^{-(1-\beta)}(qL)^{1-\beta} h^{1-\beta+\vartheta} - \frac{Lc}{K}$

The first term on the RHS may be substituted considering the expression for $\frac{\dot{c}}{c}$ Therefore we have:

$\frac{\dot{K}}{K} = \frac{\sigma\gamma + \rho}{\beta} - \frac{Lc}{K}$ Taking logarithms and differentiating with respect to time we get: $\frac{\dot{K}}{K} = \gamma + n$

ters which determine the growth rate in [2.46] may be obtained from the Hamilton conditions. In fact, from [2.42''] we have

$$(2.47)\quad \frac{m}{l} = \frac{\varepsilon}{AK^{\beta}(qL)^{-\beta}Lh^{\vartheta-\beta}}$$

Again using logarithms and differentiating with respect to time we get

$$(2.48)\frac{\dot{m}}{m} + \beta\gamma + n + (\vartheta - \beta)\frac{\dot{h}}{h} = \frac{\dot{l}}{l}$$

From equation [2.42'''] we note that $\frac{\dot{m}}{m} = -(\rho + \gamma\sigma)$, while from [2.42''] and [2.42''''] we may obtain $\frac{\dot{l}}{l} = -\varepsilon$. Therefore we can substitute these values in [2.48] to describe the parameters which define the growth rate of human capital

$$(2.49)\quad \frac{\dot{h}}{h} = \gamma_h = \frac{(1-\beta)(\varepsilon - (\rho - n))}{\sigma(1-\beta+\vartheta) - \vartheta}$$

If there is no external effect (ϑ =0), the growth rate is

$$(2.50)\quad \gamma = \gamma_h = \frac{\varepsilon - (\rho - n)}{\sigma}$$

This growth rate coincides with the optimal growth rate. If $\vartheta > 0$, equation [2.49] holds and hence we have $\gamma > \gamma_h$. This will induce higher growth of physical capital compared with human capital. In a market economy, therefore, with a positive external effect individuals will invest in human capital at a lower rate than would be socially optimal. It is however worth noting that the external effect on human capital is not necessary to determine the endogenous growth rate of the economy. This latter is positively influenced by the parameter which defines the productivity of human capital, the growth rate of the labour force and the intertemporal elasticity of substitution. The growth rate is negatively influenced by the discount rate.

2.3.3 Endogenous Growth and Research and Development

In this type of models knowledge accumulation explicitly depends on the amount of resources allocated to inventive activity. A common framework for the recent models described by Romer (1990a, 1990b, 1991) and Grossman-Helpman (1991, 1992) is the original work by Shell (1967). The economy is again represented through the aggregate production function

$$(2.51)\quad Y = f(K(t), L(t), A(t))$$

where K and L are respectively the capital stock and the labour input. A is the aggregate stock of knowledge. The evolution of A is given by the following equation

$$(2.52) \quad \dot{A} = \delta y_r(t)Y - \lambda_c A$$
$$0 < \delta \leq 1$$
$$0 \leq y_r \leq 1$$
$$\lambda_c \geq 0$$

where δ is a coefficient which reflects the success of the research activity, y_r indicates the proportion of output allocated to inventive activity and λ_c is the rate at which technological knowledge is depreciated.

The aggregate stock of capital evolves according to

$$(2.53) \quad \dot{K} = s(t)[1 - y_r(t)]Y - \lambda K$$

where s represents the propensity to save and λ is the capital depreciation rate. We focus on the accumulation of K and A; it is therefore assumed that the labour force is constant and normalised to one. In a decentralised economy the accumulation process may be obtained from the system [2.52] [2.53].

In an optimal control framework we have

$$(2.54)\quad Max\int_0^{\infty} U[(1-s)(1-y_r)Y]e^{-\rho t}\,dt$$

$$(2.54')\qquad \dot{A} = \delta y_r Y - \lambda_c A$$

$$(2.54'')\qquad \dot{K} = s(1-y_r)Y - \lambda K$$

The usual Hamilton conditions may be derived. However, it must be stressed that when there are two state variables (A and K), the solution of the problem is not simple. Shell does not give an explicit solution; however, he shows how A and K tend to a specific constant, respectively $\bar{A}$ and $\bar{K}$.

This result is not consistent, since bounded technological progress can only guarantee a constant income level which therefore remains steady. This criticism, discussed in Kzuo Sato (1965), is based, in particular, on the specification of A. In fact, if [2.52] is rewritten as

$$(2.55)\quad \dot{A} = \delta y_r A - \lambda_r A$$

or

$$(2.56)\quad \frac{\dot{A}}{A} = \delta y_r - \lambda_r$$

then there is no longer an upper bound to knowledge as long as $\delta y_r - \lambda_r > 0$.

Romer (1990a, 1990b) reconsiders this argument, which is the crucial element of his model of endogenous technical progress.

In the Romer model, the output of the sector which produces knowledge is a partially excludable good. It should be borne in mind that a good is rival if its use by an individual or firm precludes its use by another. The opposite definition applies for non-rivalry. A good is excludable if the owner can prevent others from using it. Public goods are, by definition, both non-rival and non-excludable. The Romer model separates the rival and non rival component of knowledge. The former is proxied by human capital used in the production of consumer goods, while the latter is proxied by the stock of knowledge incorporated in the designs of the existing capital goods.

The economy is represented by three sectors:

a) the final goods sector;

b) the research sector;

c) the sector which produces capital goods.

In the first sector the production function considers a multiplicity of capital goods using a representation taken from Dixit and Stiglitz (1977):

$$(2.57)\quad Y = g(L, H_y)\sum_{i=1}^{\infty} x(i)^{\phi}$$

where Y is final output, which is a function of human capital H_y, physical labour L, and physical capital. In this case, instead of a single capital good, as in the traditional neo-classic models, capital is here represented by an infinite list of producer durables

$x = \{x_i\}_{i=1}^{\infty}$. The production function is homogeneous of degree one. The function $g(H_y, L)$ is therefore homogeneous of degree $1 - \phi$.

The production function describes the technology of a representative firm, within a competitive market.

The research sector produces knowledge, which is incorporated in designs then sold to the sector which produces intermediate goods. The production function in this sector considers the production of designs at time t as a linear function of human capital (H_a) and the existing stock of knowledge (A)

$$(2.58) \quad \dot{A} = \delta H_a A$$

where δ $(\delta > 0)$ is a parameter reflecting the productivity of human capital in the research activity. The sector which produces intermediate goods cannot be described in terms of a representative firm. For each capital good (i) there is a distinct firm which therefore acts as a monopolist.

A firm in the manufacturing sector may convert μ units of final output into a unit of intermediate good. The aggregate measure of capital (K) may be defined as follows:

$$(2.59) \quad K = \mu \sum_{i=1}^{A} x_i$$

where μ represents the cost (in terms of final output) of producing one unit of capital good *(i)*. The total amount of human capital H is the sum of human capital in manufacturing (H_y) and human capital employed in the research sector (H_a.). It is also assumed that the labour force is constant, implying that H and its components are constant as well.

It is then assumed that the different types of capital goods are all used at the same level x^* and that the index i may be represented through a continuous variable. Equations [2.57] and [2.59] may be rewritten as follows:

$$(2.60) \quad Y = g(H_y, L)\int_0^A x(i)^{\phi} di = g(H_y, L)A\left(\frac{K}{\mu A}\right)^{\phi}$$

where $\quad x^* = \dfrac{K}{\mu A}$

and

$$(2.61) \quad K = \mu A x^*$$

The only variable which varies over time is A, i.e., the stock of knowledge proxied by the number of designs invented in the research sector. The growth rate of output will therefore be equal to the growth rate of A, which is constant and determined by human capital allocated to the research sector (H_a) and by the productivity parameter

δ. Due to the stationarity of the model the values of H_a and H_y are constant; however, the value of H_a is endogenously determined, thus also determining the growth rate of the economy.

The labour market must clear for H_a and H_y to remain constant. and, therefore, returns on human capital employed in the manufacturing sector and in the research sector must be equal. In the manufacturing sector returns on human capital are given by the marginal productivity rule. We therefore have

$$(2.62)\quad W_{h_y} = g_{h_y} A(x^*)^{\phi}$$

where W_{hy} is the remuneration of human capital and $g_{hy}A(x^*)^{\phi}$ is its marginal productivity. In the research sector, returns to human capital depend on the rent which can be extracted from a patent on an invented capital good. Thus we have

$$(2.63)\quad W_{h_a} = P_a \delta A$$

where P_a is the present value of the monopoly rent which can be extracted by researchers and δA is the number of designs produced per unit time per unit human capital. The problem is easily solved if one thinks of the demand and supply for durables. Demand is given by the condition for profit maximisation for the representative firm

$$(2.64) \quad Max\int_0^A (g(H_y, L)x(i)^\phi - p(x(i))x(i))di$$

and therefore

$$(2.65) \quad p(x(i)) = \phi g(H_y, L)x(i)^{\phi-1}$$

On the supply side, given the demand function, the problem for the single monopolist which produces capital good *(i)* is

$$(2.66) \quad Max\int_0^A [p(x(t))x(t) - r(t)\mu x(t)]e^{\int_0^t r(s)ds} dt$$

where $r\mu(t)$ is the rental cost of capital used for the production of $x(i)$. This problem is, however, easily solved due to the stationarity of the model. Indeed, r, $x(i)$ and ρ are constant in equilibrium. The cost of a patent P_a will be defined in equilibrium by

$$(2.67) \quad P_a = x^* rm\frac{1-f}{f}$$

and the value of x^* is determined by

$$(2.68)\quad x^* = \left(\frac{g(H_y, L)\phi^2}{r\mu} \right)^{\frac{1}{1-\phi}}$$

The conditions for the equilibrium in the labour market are

$$(2.69)\quad \delta^{-1} r g_{h_y} = g(H_y, L)(1-\phi)\phi$$

If for the sake of simplicity and without loss of generality we explicit the function $g(H_y,L)$ as

$$(2.70)\quad g(H_y, L) = H_y^{\alpha(1-\phi)} L^{(1-\alpha)(1-\phi)}$$

the value of H_a may be endogenously determined.. If we take preferences as being exogenous, this value will be given by

$$(2.71)\quad H_a = H - \frac{ra}{df}$$

If we endogenise preferences, the value of H_a is determined by[10]

[10] Preferences are easily endogenised through the usual intertemporal maximisation: $Max\ (C^{1-\sigma}/1-\sigma)e^{-rt}$ This also makes the interest rate endogenous. From the Hamiltonian conditions we get: $r = \sigma \frac{\dot{C}}{C} + \rho$

$$(2.71') \quad H_a = \frac{H - \left(\frac{ar}{fd}\right)}{1 + \left(\frac{sa}{f}\right)}$$

In both cases the result is crucial for it shows that the balanced growth rate depends on the allocation of H_a, which is in turn obtained from the equilibrium conditions in the labour market and from the parameter δ, which represents the productivity of the human capital employed in the research sector. Equation [2.71] suggests that a decrease in the interest rate causes an increase in H_a and therefore has a positive effect on the long-run growth rate. From equation [2.72] the impact of the interest rate is obtained through the parameters ρ and σ. It is worth noting that the parameter μ, which defines the production cost of capital goods, does not affect the equilibrium value of H_a and therefore the growth rate. This means that any investment subsidies, which bring about a reduction of the production cost of capital goods, have no effect on economic growth. This is due to the equilibrium conditions in the labour market. Human capital in the research sector must compete with human capital in manufacturing and returns on both inputs must, therefore, be equal in equilibrium. A subsidy which reduces the value of μ determines a higher value of x^* (from equation 2.67). An increase in x^* has a positive effect on the marginal productivity of H_y and therefore on its remuneration. On the other hand, the demand for capital goods increases and returns to human capital in research increases as well. These effects offset each other causing the result given by equation [2.72].

The growth rate determined through this mechanism is lower than the socially optimal growth rate, as returns on human capital in the research sector do not correspond to their optimal level, causing, therefore, an underallocation of resources in this sector. This depends, on the one hand, on externality in the research sector, as the aggregate stock of knowledge grows as new inventions are discovered without any remuneration (due to the non-excludability hypothesis). On the other hand, the purchase of designs is made by a single monopolist producing intermediate goods. This causes a difference between the remuneration of the input used (the price of the patent) and the marginal productivity of human capital in the research sector.

A socially optimal solution may be achieved through a subsidy to the research sector to balance the difference between the marginal productivity of human capital and the corresponding remuneration.

2.3.4 Product Variety

A re-formulation of the previously analysed models is derived from the studies of Grossman and Helpman (1991a, 1991b, 1992). This formulation is based on the hypothesis of differentiated output (of consumer or intermediate goods) and uses the specification of monopolistic competition adopted in Dixit and Stiglitz (1977). In this model each firm holds the technology for the production of a single horizontally differentiated good. The firm may also invest in Research and Development to produce new differentiated goods.

The model is characterised by an aggregate demand side defined by

$$(2.72)\quad C=\left[\int_0^n x(j)^{\alpha}\,dj\right]^{\frac{1}{\alpha}}$$

$$0<\alpha<1$$

where $x(j)$ is the quantity of good x of the variety j. On the supply side, each firm holds the technology for the production of a single variety, for which it has a monopolistic power. It is assumed for simplicity that each variety needs a labour unit for each unit of output produced. The demand function [2.72] implies that: $MR(j) = \alpha p(j)$, where $MR(j)$ is the marginal revenue and $p(j)$ the price of variety (j). If the marginal cost MC is equal to the wage rate w for all varieties and if $MR(j) = MC(j)$ the price of the single varieties will be the same

$$(2.73)\quad p=\frac{w}{\alpha}$$

Given the price rule, operating profits per variety of good are defined by

$$(2.74)\quad \pi=(1-\alpha)\frac{pX}{n}$$

where X represents aggregate output and n the number of varieties. In a dynamic framework, monopolistic competition implies an entry condition determined by a no-arbitrage rule

$$(2.75)\quad \frac{\pi}{\vartheta}+\frac{\dot{\vartheta}}{\vartheta}=r$$

ϑ represents the value of a firm, which is equivalent to the present value of the profits gained at any time t. In other words, ϑ is given by

$$(2.76)\quad \vartheta=\int_{t}^{\infty} e^{-\int_{t}^{\tau} r(s)ds}\,\pi(\tau)d\tau$$

where π represents the profits flow and r the discount rate. The no-arbitrage condition establishes that the rate of profit and the rate of capital gain are equal to the nominal interest rate. A potential entrepreneur who wants to invest in R&D to develop a new variety of product expects a profit equal to ϑ and will invest if the relevant cost does not exceed this value. Hence ϑ represents the value of the innovation and may be described by

$$(2.77)\quad \vartheta = \frac{wb}{A_n}$$

where b is a parameter which reflects labour productivity, w is the wage rate and A_n is the stock of knowledge. Assuming that A_n is proxied by the cumulated experience in R&D measured by the number of varieties which have been invented (n), we may write [11]

$$(2.78)\quad \vartheta = \frac{wb}{n}$$

The equilibrium condition in the labour market requires that employment in R&D and in the manufacturing sector be equal to the aggregate supply of labour

$$(2.79)\quad \frac{b}{n}\dot{n} + X = L$$

where b/n represents the amount of work needed for an innovation; $\dot{n}$ is the number of innovations at time t and X the amount of labour allocated to the manufacturing sector.

If it is assumed that consumer preferences are described by the usual utility function $u = \frac{c^{1-\sigma}}{1-\sigma}$, the growth rate of C may be derived from

[11] This hypothesis is the same as that used in the Romer model of section 2.1.3.

$$(2.80)\quad \frac{\dot{C}}{C} = \frac{1}{\sigma}\left[r - \rho - \frac{\dot{p}_c}{p_c}\right]$$

where p_c is the price of final output (in equilibrium the price is identical for all varieties). Given the equilibrium condition in the labour market and the non-arbitrage condition, it is possible to show that the economy is characterised by the following growth rate[12]

$$(2.81)\quad \gamma_n = \frac{\left[(1-\alpha)\frac{L}{b} - \alpha\rho\right]}{\alpha + (1-\alpha)\sigma}$$

where ρ is the rate of time preference, b is the parameter which reflects labour productivity and σ is the inverse of the elasticity of intertemporal substitution. It is worth noting that γ_n increases if:

---

[12] Consider the following equations: $a\gamma_n + X = L$; $\frac{\pi}{\vartheta} + \frac{\dot{\vartheta}}{\vartheta} = r$. The first equation represents the resource constarint in the labour market, while the second describes the no-arbitrage. Since $\vartheta = \frac{wb}{n}$ and $p_c = \frac{w}{\alpha}$. and taking the wage rate as the numeraire, we have: $p_c = \frac{1}{\alpha}$ and therefore: $\vartheta = \frac{b}{n}$. This implies that: $\frac{\dot{\vartheta}}{\vartheta} = -\gamma_n$. In addition we have: $\frac{\pi}{\vartheta} = (1-\alpha)\frac{X}{b\alpha}$. From the equation which defines the demand for goods we get: $\frac{\dot{C}}{C} = \frac{(1-\alpha)}{\alpha}\gamma_n$ and $\frac{\dot{p}_c}{p_c} = \frac{-(1-\alpha)}{\alpha}\gamma_n$. The interest rate is therefore defined by: $r = \rho + \gamma_n \frac{1-\alpha}{\alpha}(\sigma - 1)$. Substituting into the equation which defines the no-arbitrage condition we get equation (2.80).

a) the size of the labour force *(L)* is greater (scale effect);

b) the rate of time preference is lower;

c) the degree of monopolistic power ($1/\alpha$) is greater;

d) the elasticity of intertemporal substitution ($1/\sigma$) is greater.

These results are clearly shown in Figure 2.3., where the steady state conditions are represented. The *RR* curve represents the resource constraint, while the *AA* curve represents the no-arbitrage condition. The *RR* curve has a negative slope as an increase in the innovation rate (γ_n) implies greater employment in the R&D sector and therefore a decrease in employment in manufacturing. The *AA* curve has a positive slope as an increase in the innovation rate brings about an increase in the effective capital cost, determined by a higher interest rate and a faster depreciation of the value of the firm. A higher profit rate is therefore needed to undertake the R&D activity. The intersection between the two curves represents the steady state equilibrium.

Figure 2.3a. shows how growth is constrained, on the one hand, by the availability of resources and, on the other, by market incentives. An expansion of the available resources moves the *RR* curve upwards; a lower rate of time preference moves the *AA* curve downwards, while a greater degree of monopolistic power moves the *AA* curve downwards, as in the case of a higher intertemporal elasticity of substitution.

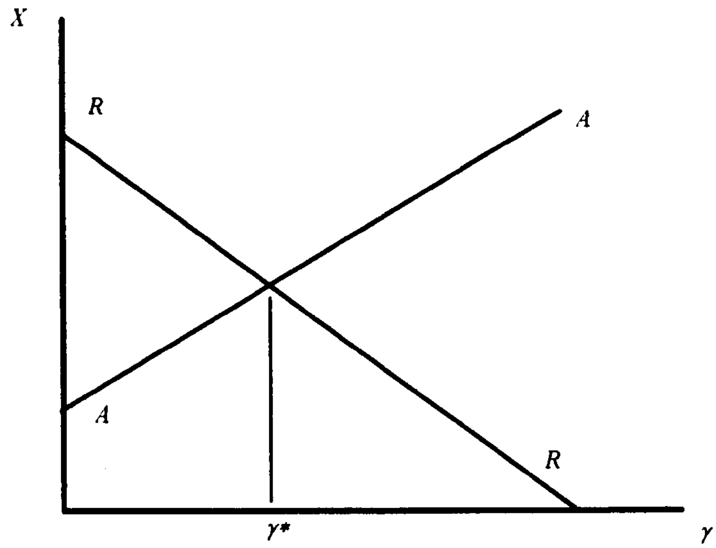

Figure 2.3a

It is worth noting that the model defines a positive rate of innovation if $L/b > \alpha\rho/(1 - \alpha)$ (from equation [2.81]). If this condition does not hold, there is no endogenous growth (γ_n) = 0. The cost of innovation is so high that it discourages any innovation. The solution implies that all the resources are allocated to the production of the existing varieties of goods, without further innovation (new varieties). Figure 2.3a must be modified as follows:

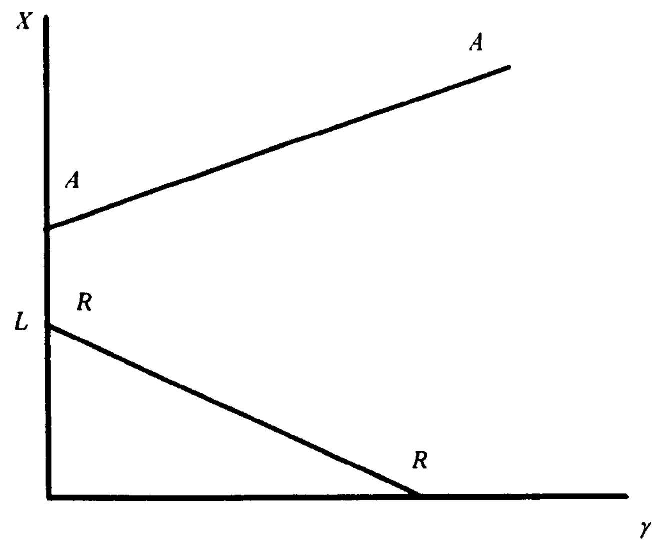

Figure 2.3b

This analysis, which deals with the production of differentiated final goods, may be extended to the case of differentiated productions of intermediate goods. The model may also be extended to the case where the increase in quality of new products is taken into account. In this case, the high quality products substitute for the low quality ones. This means that the producers of the low quality goods will not gain any more positive profits and that therefore monopolistic power is not maintained for an infinite time, as in the case of horizontally differentiated products.

The arbitrage condition is modified to take into account the risk of the investment in R&D depending on the likelihood of losing monopolistic power when a product of better quality enters the market. The results of the determinants of the growth rate of the economy are, however, similar to those previously analysed.

As in the Romer model the difference between the balanced and optimal growth rate lies in the external effect produced in the R&D sector. Indeed, the stock of knowledge grows as new varieties of products are created by single researchers without any corresponding remuneration. A Pareto efficient solution may be attained by introducing a subsidy to the R&D sector to take into account this spill-over effect and to restore equilibrium between the private and social remuneration of labour in the research sector.

A further development of these R&D models is given in the analysis by Aghion and Howitt (1992), of which we mention the main hypotheses and conclusions.

The output of research activity is made stochastic through inventions which arrive following a Poisson stochastic process. In addition, a sort of Shumpeterian hypothesis (creative destruction) is introduced, in that the successful R&D activity makes the previous inventions unprofitable. This innovative mechanism finally determines endogenous economic cycles. The model, while improving on previous R&D models, does not consider capital accumulation, as physical capital is not considered in the production functions of the three sectors which define the economy.

2.3.5 Empirical Evidence

On theoretical grounds the neo-classic models previously analysed have furthered the debate regarding the long-run determinants of growth.

Despite this theoretical improvement, empirical tests in this line of research are still controversial. However, there have been some recent improvements in techniques and in the quality of the data sets. Nevertheless, general dissatisfaction persists, particularly regarding the robustness of the results and the explanatory capacity of the adopted empirical models.

Two different approaches have been used for the empirical tests. The first makes use of a historic approach, identifying all those cases where external economies deriving from the use of certain capital goods have involved significant increases in productivity growth (Rosenberg 1986, Caballero-Lyons 1991).

The second approach uses econometric analysis based on cross-country data, which aims to establish the significance of appropriate explanatory variables as determinants of the growth rate.

We will focus on this second approach, which is the empirical counterpart of the theoretical models analysed in the previous sections. The core empirical literature includes the studies by Romer (1990b), De Long-Summers (1991, 1992), Barro and Sala-i-Martin (1992), Fischer (1992), Mankiw, Romer and Weil (1992), Jones (1995).

In the model proposed by Romer (1990a, 1990b), the crucial variable affecting the long-run growth rate is the human capital employed in the research sector. The empirical test is, however, indirect. It is worth recalling the fundamental equation of the theoretical model, and then we shall discuss the empirical results. From section (2.3.3) the value of H_a, i.e., the human capital allocated to R&D, is determined by

$$(2.82)\quad H_a = \frac{H - (\frac{\alpha\rho}{\phi\delta})}{1 + (\frac{\alpha\rho}{\phi})}$$

This result crucially depends on the assumption that the function $g(H_y,L)$, which appears in the aggregate production function, is of the type

$$(2.83)\quad g(H_y, L) = \left[\alpha H_y^{\beta} + (1-\alpha) L^{\beta}\right]^{\frac{1-\phi}{\beta}}$$

If the parameter β tends to zero, we have the usual Cobb-Douglas production function

$$(2.84)\quad g(H_y, L) = H_y^{\alpha(1-\phi)} L^{(1-\alpha)(1-\phi)}$$

In this case, even assuming some exogenous variations in the labour force (L), there are no effects on the equilibrium value of H_a and, therefore, on the growth rate. In fact, an increase in L causes an increase in the marginal productivity of human capital in the manufacturing sector and, therefore, an increase in its remuneration. It also causes an increase in the monopoly profits deriving from the production of each new capital good. The price of each design therefore increases, thus causing an increase in returns in the research sector; with the adopted Cobb-Douglas specification these variations offset each other, thus leaving the market equilibrium unchanged. In this case the increase in L has no effects on the long-run growth rate.

On the other hand, assuming that the value of the parameter β is different from zero, a variation of L influences H_a. In this case we have

$$(2.85)\quad r = \delta\phi(H - H_a) + \frac{\delta\phi(1-\alpha)}{\alpha} L^{\beta}(H - H_a)^{1-\beta}$$

It may be argued that if H and L are complements (if β is below zero) an increase of L causes a reduction of H_a and therefore a reduction in the long-run growth rate.

The empirical model takes into consideration the basic aggregate production function [2.60], which may be rewritten as a function of A and K

$$(2.86)\quad Y = g(H_y, L)A\left(\frac{K}{\mu A}\right)^{\phi} = g\left(\frac{H_y}{L}, 1\right)L^{1-\phi}A\left(\frac{K}{\mu A}\right)^{\phi}$$

Using logarithms and differentiating with respect to time gives

$$(2.87)\quad \frac{\dot{Y}}{Y} = \frac{d}{dt}ln\left[g\left(\frac{H_y}{L}, 1\right)\right] + (1-\phi)\frac{\dot{L}}{L} + (1-\phi)\frac{\dot{A}}{A} + \phi\frac{\dot{K}}{K}$$

Denoting the capital depreciation rate as λ, the investment-output ratio will be linked to K by the relation

$$(2.88)\quad \frac{\dot{K}}{K}=\left[\left(\frac{I}{Y}\right)\left(\frac{Y}{K}\right)\right]-\lambda$$

Substituting [2.88] in [2.86] yields:

$$(2.89)\quad \frac{\hat{\dot{Y}}}{Y}=\frac{d}{dt}\,ln\left[g\left(\frac{H_y}{L},1\right)\right]+(1-\phi)\frac{\dot{L}}{L}+(1-\phi)\frac{\dot{A}}{A}+\phi\frac{Y}{K}\frac{I}{Y}-\phi\lambda$$

From the hypotheses of the theoretical model it may be argued that the investment-output ratio does not affect the growth rate of A; on the other hand, L has a negative effect on this variable.

From equation [2.89] the impact of the investment-output ratio and the size of the labour force (L) may be derived. However, one needs to assume, on the one hand, that the ratio $H_y L$ remains substantially constant over the sample period and, on the other hand, to consider the bias deriving from the omission of the variable A, which represents the stock of knowledge. The results obtained by Romer for the period 1960-85 and for a group of 112 countries are summarised in Tables 2.1 and 2.2.

Table 2.1 ***Dependent variable: annual mean growth rate of GDP per capita, 1960-85. OLS estimates.***

	Coeff.	**t-stat**
Const.	2.20	2.78
POPGR.	0.968	4.71
Y	- 0.0002	- 2.55
INV	0.182	6.67
GOV	- 0.099	- 3.57
DUM1	- 1.27	- 3.13
DUM2	- 1.24	- 2.96
R2adj.	0.147	
SE	1.436	
VM	4.07	
SD	1.88	

Table 2.2 ***Dependent variable: annual mean growth rate of GDP per capita, 1960-85. OLS estimates***

	Coeff.	**t-stat**
Const.	0.949	1.00
POPGR	0.885	4.33
Y	- 0.0003	- 2.83
INV	0.422	3.93
INV2	- 0.0076	- 2.31
GOV	- 0.110	- 3.99
DUM1	- 1.04	- 2.53
DUM2	- 1.25	- 3.04
R2adj.	0.440	
SE	1.41	
VM	4.07	
SD	1.88	

Legend: POPGR = average annual rate of growth of the population:
Y = mean income; INV = ratio of investment (public and private) to GDP; GOV = ratio of public expenditure to the GDP (excluding public investment); INV2 = square root of INV; DUM1 = Dummy for African countries; DUM2 = Dummy for South American countries.
SE = standard error of regression; VM = mean value of dependent variable; SD = standard deviation of dependent variable. The number of countries considered is 112.
Source: ROMER (1990b) pages 358-59.

We concentrate in particular on the investments variable, as it plays a crucial role in the theoretical model.

The impact of the investments-output ratio crucially depends on the sources of its variations. From the theoretical model it may be argued that only those variations induced by a growth of the stock of knowledge (A) have a positive impact on the long-run growth rate. In other words, only the innovative effort (proxied by the R&D activity) which leads to new investments produces long-run effects on growth.

In the proposed estimates, both private and public investments are considered, while the population growth is a proxy of the labour force growth rate. Romer himself stresses that this test represents an empirical exercise, rather than a real test of the proposed theoretical model. The coefficients of the parameters shown in tables 2.1 and 2.2 are not robust to modifications in the adopted specifications. However, some general comments may be considered:

a) the coefficient of the investments ratio is significant in the different specifications adopted. This coefficient is the synthesis of the two previously underlined effects; it includes the effects of the variation of the stock of knowledge (A) and the autonomous effects of the variation of the investment-output ratio;

b) the growth rate of population is used as proxy of the labour force growth rate; its coefficient is unexpectedly high. This result is partially explained by the weight in the considered sample of developing countries, where the mechanism through which an increase in L leads to a reduction of the growth rate does not hold. In addition, these countries have not yet passed through the phase of demographic transition, typical of the more industrialised countries. It is therefore possible that a higher per capita income growth rate may be associated to an increasing population growth rate;

c) the significance of the dummies which represent the African and South American countries underlines the omission of explanatory variables in the adopted specification and is one of the main drawbacks of the empirical tests of the new growth theory, i.e., the impossibility of fully assessing the growth determinants within information sets which are deeply heterogeneous.

The analysis by Barro (1990, 1991) follows this line of research. Although in this case the theoretical model is not formally explained, the new growth theory is however assumed as the theoretical benchmark. This empirical test establishes the relationships between the growth rate, the ratio of private investment to GDP, the fertility rate and the availability of human capital. The main significant relationships identified in the work of Barro show that:

a) the growth rate is positively correlated to the initial level of human capital proxied by different measures of school enrolments. This evidence is associated to the negative correlation between the growth rate and the initial level of per-capita income. The relatively poorer countries, therefore, tend to catch-up the rich economies if they have a high per-capita human capital level compared with their per-capita income level. However, the reverse relationship does not hold.

b) countries with a high level of human capital also show a relatively lower fertility rate and a high investment-GDP ratio.

c) the growth rate and the ratio of private investment to GDP are negatively correlated to the ratio of public expenditure to GDP. This may be explained by arguing that a high level of public expenditure may also involve high tax levels, which may have distorsive effects;

d) the relationship between the growth rate and the ratio of public investment is not robust. This may be explained by using the typical crowding-out argument, in that higher interest rates corresponding to high public expenditure may negatively affect the growth rate of GDP.

In an augmented version of the Solow model to include human capital, Mankiw, Romer and Weil (1992) argue that this traditional model may explain the variation of the growth rate in a cross section of countries.[13]

The estimated model considers the following equation showing aggregate output:

$$(2.90)\quad Y(t) = K(t)^{\alpha} H(t)^{\beta} \big(A(t)L(t)\big)^{1-\alpha-\beta}$$

where human capital H has been added to physical capital K and labour L; A represents the level of technology.

The dynamic path of the economy is described by the equations which represent the accumulation of physical and human capital respectively

$$(2.91)\quad \dot{k} = s_k y(t) - (n + g_a + \lambda)k(t)$$
$$(2.92)\quad \dot{h} = s_h y(t) - (n + g_a + \lambda)h(t)$$

[13] The estimates refer to a group of 121 countries and consider the mean growth rate over the period 1960-85.

where $y = Y/AL$, $k = K/AL$ and $h = H/AL$. The parameters n, g_a and λ are respectively the exogenous labour force growth rate, the productivity growth rate and the capital depreciation rate, while s_k and s_h are respectively the income invested in physical and human capital as a proportion of total income.

It is also assumed that $\alpha + \beta < 1$; in other words, it is assumed that there are decreasing returns in the reproducible inputs [14].

From the equations [2.91] and [2.92] the steady state is defined by

$$(2.93)\quad k^* = \left(\frac{s_k^{1-\beta} s_h^{\beta}}{n+g+\lambda}\right)^{\frac{1}{(1-\alpha-\beta)}}$$

$$(2.94)\quad h^* = \left(\frac{s_k^{\alpha} s_h^{1-\alpha}}{n+g+\lambda}\right)^{\frac{1}{(1-\alpha-\beta)}}$$

Substituting these equations in [2.90] and taking logarithms we have[15]

$$(2.95)\quad ln\left(\frac{Y(t)}{L(t)}\right) = ln\, A(0) + gt - \frac{\alpha+\beta}{1-\alpha-\beta} ln(n+g+\lambda) + \frac{\alpha}{1-\alpha-\beta} ln(s_k) + \frac{\beta}{1-\alpha-\beta} ln(s_h)$$

This equation shows the growth rate of per capita income in steady-state as a function of the parameters which define the growth rate of the population, the accumula-

[14] This condition is necessary for the existence of a steady-state.

[15] It should be borne in mind that the labour force and productivity grow at the rates n and g_a. Hence we have: $L=L_0e^{nt}$ e $A=A_0e^{gat}$

tion rate of physical and human capital and the depreciation rate of physical capital. This equation shows how the coefficients of physical capital accumulation and population growth rate variables differ if human capital is ignored in the specification. Table 2.3. shows the results of the estimates obtained by Mankiw, Romer and Weil, confirming the hypothesis that the augmented Solow model may significantly explain the variations of per-capita GDP growth rate among different economies. However, the model fits better in the whole sample of countries than in the OECD countries sub-sample alone.

Table 2.3 ***Solow model augmented for human capital. Dependent variable: natural log of GDP per capita in 1985.***

	(1)		(2)		(3)	
	Coeff.	**t-stat**	**Coeff.**	**t-stat**	**Coeff.**	**t-stat**
Cost.	6.89	5.86	7.81	6.56	8.63	3.94
In(I/GDP)	0.69	5.31	0.70	4.67	0.28	0.72
In($n + g_a + \lambda$)	- 1.73	- 4.22	- 1.50	- 3.75	- 1.07	- 1.43
In(EDU)	0.66	9.43	0.73	7.30	0.76	2.62
R2adj	0.78		0.77		0.24	
SE	0.51		0.45		0.33	

In(I/GDP = log ratio of investment to GDP in the period 1960-85; n = mean growth rate of the labour force in the period 1960-85; $g_a + \lambda$ = 0.05; In(EDU) = natural log of the average percentage of the labour force with high school degree in the period 1960-85: (1) 98 countries excluding the oil producers; (2) 75 countries; (3) OECD countries.
Source: Mankiw, Romer and Weil (1992), page 420.

However, it must be underlined that one of the most significant drawbacks of this empirical approach concerns the assumption of the equality of the parameters in the production function of each country. The estimates are built on mean values of the variables, typically at five-year or longer intervals. In a recent work, Canning, Dunn and Moore (1995) show how the hypotheses of the equality of the parameters of the production functions is rejected in a time series framework for a wide group of countries. This hypothesis is also rejected in the context of homogeneous sub-groups (for example the OECD group), proving the robustness of this evidences. It is also tested the hypothesis that the elasticity of capital in the aggregate production function is unit against the alternative (Solow model augmented with human capital) that it is lower than unit. This hypothesis, typical of the so-called AK models (Rebelo 1991), is rejected.

Within the empirical debate, a more detailed analysis on the role of investment in the growth process has gained further attention. In particular, investment in machinery and equipment has been considered as a key variable affecting the growth rate of the economy. This variable is also more easily traceable to the theoretical models with endogenous technical progress generated by the R&D sector.

The studies of De Long and Summers (1991, 1992a, 1992b) summarise this line of empirical research, which, however, needs further testing particularly on time series grounds[16].

The link between investment in machinery and equipment and growth may also be justified following further considerations:

a) economic history has reserved a central role for the different processes of mechanisation that have taken place. The most developed countries are those which have invented and, therefore, made the first innovations, particularly in capital-intensive technologies.

[16] In the fourth chapter we will analyse this aspect in more detail, focusing particularly on causality tests.

b) the debate originated by Hirschman (1958) emphasises the crucial role of external economies (or, in the terms of the original debate, the linkages) deriving from investment. These arguments were later resumed by the new growth theory.

Table 2.4 summarises the results of De Long and Summers' estimate.

Table 2.4 ***Dependent variable: Annual mean growth rate of per-capita GDP (1960-85).***

	(1)		*(2)*	
	Coeff.	t.-stat.	Coeff.	t-stat.
$I_{im} Y$	0.302	4.137	0.219	3.174
$I_a Y$	0.019	0.36	0.097	2.425
	0.043	0.292	- 0.026	0.135
Gap	0.032	3.555	0.020	2.222
R2	0.719		0.369	
SE	0.008		0.013	
N	25		61	

Source: De Long-Summers (1992a). (1). The sample includes 25 countries which do not export oil. (2) includes the developing economies. On the whole these are economies whose productivity gap with respect to the United States is less than 20%.

The estimated equation is as follows:

$$(2.96)\quad \frac{\dot{Y}}{Y} = \alpha_0 + \alpha_1\left(\frac{I_{im}}{Y}\right) + \alpha_2\left(\frac{I_a}{Y}\right) + \alpha_3\frac{\dot{L}}{L} + \alpha_4\left[\frac{\left(\frac{Y}{L}\right)_j}{\left(\frac{Y}{L}\right)_{US}}\right]$$

The mean growth rate for each country is estimated as a function of the ratio of investment in machinery and equipment (I_{im}/Y), the ratio of total investment (excluding machinery and equipment) to GDP (I_a/Y), the growth rate of the labour force and the initial productivity gap with respect to the United States. This last variable captures the catching-up effect.

The ratio of investment in machinery and equipment shows the greatest impact among the variables used in the regression even when other control variables, such as the school enrolment ratio or continental dummies, are included.
This test underlines the key role of investment in machinery and equipment in the growth process, but without telling us anything about the possible causal link between these two variables. This problem will be analysed in depth in chapters 6 and 7.

2.4 The Convergence Hypothesis

One important implication of the neo-classic growth models (Solow (1956), Cass (1965), Koopmans (1965), is that the growth rate of per capita income is inversely related to the initial income level. This means that if the economies have similar technology and individual preferences, the poorer economies must show higher growth rates, therefore causing a convergence in income levels. This hypothesis is defined as absolute convergence, and crucially depends on the two assumptions of *a)* decreasing returns for production inputs and *b)* for the poorer economies returns on capital are greater. This hypothesis is based on some strong assumptions; it holds given the same level of technology, population growth rate, capital depreciation rate and propensity to save. If only one of these requisites is missing, the hypothesis of convergence towards a common steady state does not hold.

As a result, the concept of conditional convergence has been introduced; it is a concept which one may apply to economies which have different initial conditions of technology, preferences, the growth rate of population etc., each of which converges towards its own steady state (Barro and Sala-i-Martin 1992, 1995).

To make these concepts clearer we may use a simple formalisation and a graphic example. The aggregate production function is

$$(2.97) \quad Y = AK^{\beta}L^{\alpha}$$

In a closed economy net investments are equal to savings net of depreciation. Hence we have

$$(2.98) \quad \dot{K} = sAK^{\beta}L^{\alpha} - \lambda K$$

where λ is the depreciation rate and s is the saving rate. It is also assumed that the labour force grows at a constant and exogenous rate n and that the traditional hypothesis of constant returns to scale holds ($\alpha + \beta = 1$). In per capita terms equation [2.98] becomes

$$(2.99) \quad \dot{k} = sAk^{\beta} - (\lambda + n)k$$

Therefore

$$(2.100) \quad \frac{\dot{k}}{k} = sAk^{-(1-\beta)} - (\lambda + n)$$

The growth rate is then given by the difference between $sAk^{-(1-\beta)}$ and $(\lambda + n)$. This result is also shown in figure 2.4.

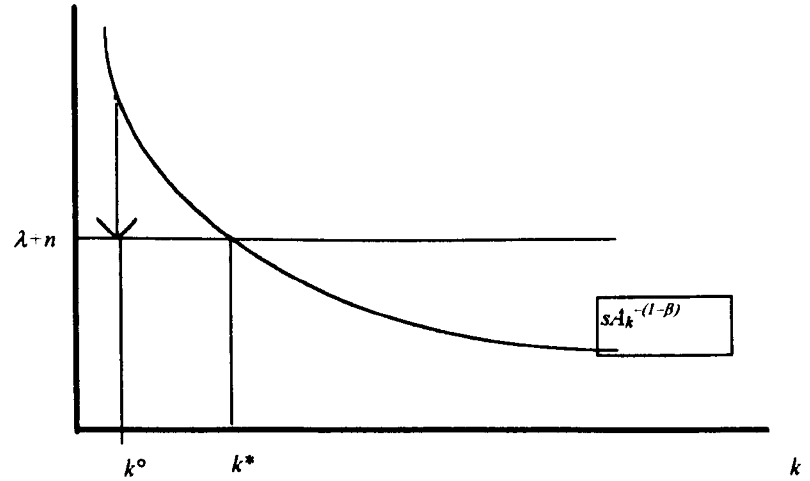

Figure 2.4 *Absolute convergence*

The function $(\lambda+n)$ is a horizontal line, since it does not depend on k. On the other hand, given the assumption of constant returns to scale ($\alpha + \beta = 1$, $\beta < 1$) the function $sAk^{(1-\beta)}$ is decreasing and asymptotically going to zero. The two curves intersect at k^*, which represents the steady state capital-labour ratio. Figure 2.4 suggests that the growth rate for an economy whose initial values are below the steady state is greater and subsequently decreasing [17]. However, as we have seen previously, this result holds if the economies differ only in the initial value of the capital-labour ratio. Technology, the saving rate, the depreciation rate and the growth rate of the labour force must be the same. Under these circumstances we have absolute convergence.

Figure 2.5 illustrates the case of conditional convergence. In this case two economies with different initial endowments of capital and different saving rates are compared.

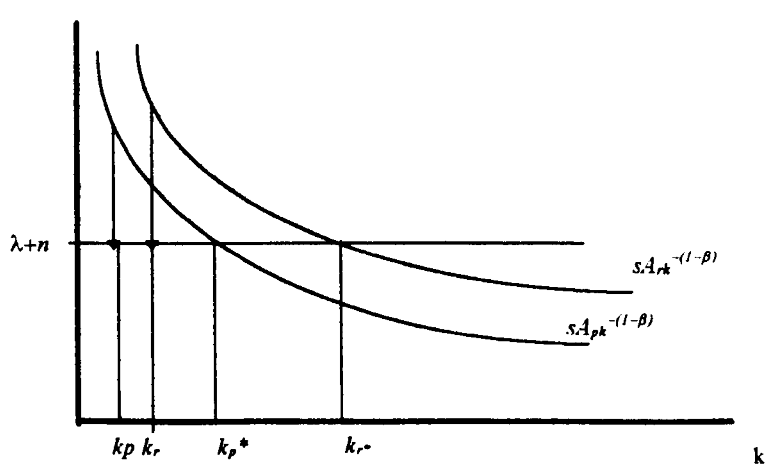

Figure 2.5 *Conditional convergence*

[17] This means that an economy with a lower capital-labour ratio (poor economy) will grow faster, all other contions being equal, than a rich economy with a higher capital labour ratio.

The economy with a lower capital-labour ratio may be considered as a developing economy; in contrast, the economy with a higher capital-labour ratio is an advanced economy. The developing economy also has a lower saving rate. This means that the steady state value of the capital-labour ratio will be lower than that of the advanced economy. As is easily observed, in this case there is not absolute convergence. Each economy converges towards its own steady state at a decreasing rate in both cases.

The empirical tests in this framework are controversial. The predictions of the neo-classic model generally imply an inverse and significant correlation between the initial per capita income levels and the growth rates in a cross-section of countries. This relation is also defined as β convergence. In addition, we can also consider a measure of convergence which refers to the change in the dispersion of per-capita income for a certain group of economies in a given time interval (σ convergence).

These two concepts can be analysed in more detail. The first concept refers to the value assumed by the coefficient β in a cross section regression of N economies

$$(2.101) \quad ln(\frac{y_{it}}{y_{it-1}}) = \alpha - \beta\, ln(y_{it-1}) + \varepsilon_{it}$$

The term on the *LHS* of [2.101] represents the growth rate of economy i and $ln(y_{it})$ is the income level (in logarithmic terms). The convergence hypothesis implies that the value of β must be $0 < \beta < 1$. In other words, the growth rate is inversely related to the initial income level; this means that poorer economies grow at higher rates than advanced economies following a path towards a common steady state.

The condition $\beta < 1$ rules out the possibility of overshooting; in other words, it excludes the possibility that poorer economies systematically overtake advanced economies in the future.

The definition of absolute convergence deals with the univariate regression [2.101], while the definition of conditional convergence deals with a multiple regression in which the coefficient β is estimated conditional on other explicitly introduced factors.

The term ε_{it} captures all the other factors that can influence growth, such as temporary shocks to the production function or modifications in the propensity to save.

If it is assumed that ε_{it} is white noise, it is possible to represent the subsequent dispersion of per-capita income by the equation

$$(2.102) \quad \sigma_t^2 = (1/N)\sum_{i=1}^{N}\left(ln(y_{it}) - \mu_t\right)^2$$

where μ_t is the mean of the sample. For large N the sample variance approximates to the population variance. Equation [2.102] may be used to proxy the of $\sigma_t^{\ 2}$. We thus have

$$(2.103) \quad \sigma_t^2 \cong (1-\beta)^2 \sigma_{t-1}^2 + \sigma_\mu^2$$

This is a first order difference equation which is stable if $0 < \beta < 1$. In other words, if there is no β convergence, the per-capita income dispersion grows; this means that β convergence is a necessary condition for σ convergence.

The steady state value of $\sigma_t^{\,2}$, which is given by [2.103], decreases as β increases, while it is positively related to the growth of σ_μ

$$(2.104)\quad \sigma^{*2} = \sigma^2{}_\mu \,/\, (1-(1-\beta)^2)$$

The solution of the difference equation [2.103] allows to further describe the effects of β on the dispersion of per-capita income. The solution of the equation [2.103] is given by

$$(2.105)\quad \sigma_t^{\,2} = \left(\sigma_0^{\,2} - \sigma^{*2}\right)\left((1-\beta)^2\right)^t + \sigma^{*2}$$

where $\sigma_0^{\,2}$ is the initial value of $\sigma_t^{\,2}$.

If $\beta > 0$, i.e., the hypothesis of β convergence holds, the condition for the dymamic stability of the difference equation [2.103] is satisfied. However, $\sigma_t^{\,2}$ may increase or decrease in its approach to the steady state according to whether the initial value of σ^2 is higher or lower than the steady state. This means that β convergence is necessary but not sufficient to guarantee σ convergence.

It is worth noting that in the endogenous growth models, economic convergence is verified only in particular cases. The simple AK model is an example in this respect. In this case the growth rate corresponding to that of equation [2.100] is

$$(2.106)\quad \frac{\dot{k}}{k} = sA - (\lambda + n)$$

If we assume that $sA>(\lambda+n)$, we get a positive growth rate which may also be represented in figure 2.6. The absence of convergence can be easily deduced, since, for example, for two economies with different endowments of capital, the growth rate will be the same and determined by the vertical distance between the two curves sA and $(\lambda+n)$.

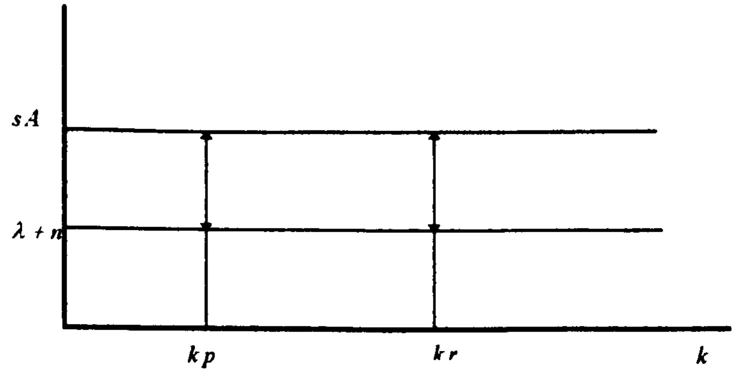

Figure 2.6 *Growth rate in the AK model*

However, even this simple endogenous growth model may predict convergence if it is assumed that the saving ratio s is a decreasing function of k or that the growth rate of the population (n) or the rate of depreciation (λ) are instead growing functions of k. In the first case we have a negative slope of the sA curve in figure 2.6, while in the other cases the slope of the capital depreciation curve becomes positive.

Convergence may also be generated within the endogenous growth models if one considers the diffusion of technology among different economies. In particular, it may be assumed that, given the technological level of a leader country, the technological level of follower countries approaches the former following a specified dynamic path. More simply, this fact may be represented through the equation

$$(2.107) \quad \frac{\dot{A}_f}{A_f} = \omega(A_l - A_f)$$

This equation suggests that the evolution of the follower's technology (A_f) is a function of the distance between its technological level and that of the leader country (A_l). In this case convergence may be also predicted to the extent to which follower's technological level catches up with that of the leader.

Following this theoretical investigation the empirical literature has tried to test the convergence hypothesis for different economies.

In an empirical study concerning the United States and a group of other countries[18] Barro and Sala-i-Martin (1992) show how absolute convergence can only be found within relatively homogeneous economies (the American states), while conditional

[18] Barro and Sala-i-Martin considers 98 countries and the growth rate between 1960 to 1985. The data set used is the Pen World Table 5.1

convergence alone is verified in their international cross section analysis. Moreover, as Barro (1991) underlines, the convergence hypothesis may be verified if the neo-classic model is modified to take into account the role of human capital. In Mankiw, Romer and Weil (1992), the Solow model augmented for human capital confirms the convergence hypothesis. A drawback of this test lies, however, in the hypotheses of constancy of the population growth rate and capital accumulation.

Recent studies by Bernard and Jones (1996a, 1996b) underline that a proper measure of convergence must be considered within an intersectoral framework. Using a panel of 14 OECD countries during 1970-1987 they show that manufacturing exhibits little evidence of labour productivity or multifactor productivity convergence, while the service sectors do converge, driving the aggregate convergence evidence.

2.5 Economic Integration and Growth

The relationship between economic integration and growth has been a crucial element in the debate among economists since the seminal analysis by Adam Smith on the role of fixed costs and the extent of the market. On historical grounds, Rosenberg (1986) shows how the diffusion of innovative ideas has played a crucial role in the economic development of modern industrial economies.

The new growth theory has tried to use these ideas to describe the long-run effects of greater economic integration. In this section we analyse this issue using as a benchmark model the R&D model described in Rivera-Batiz and Romer (1991), which is an extension of the model described in section 2.3.

The economy can be thought of in terms of two sectors. On the one hand there is the manufacturing sector, which produces final output goods and intermediate goods, and on the other hand there is the research sector which produces the designs of the new capital goods.

The production function in the manufacturing sector assumes the traditional Cobb-Douglas representation, with the characterisation used in section 2.3.3.

$$(2.108) \quad Y = H^{\alpha} L^{\beta} \int_0^A x(i)^{1-\alpha-\beta} di$$

Since the production function is the same in the sector which produces final output and intermediate goods, the manufacturing sector as a whole may be represented by equation [2.108]. For sake of simplicity it is also assumed that the relative prices of consumer and investment goods are fixed and equal to one. This simplifies the aggregate measurement of capital which is given by[19]

$$(2.109) \quad K = \int_0^A x(i) di$$

This specification implies that the inputs used for the production of a unit of the consumer good may be transferred to the production of capital goods. It is implicit, therefore, that the manufacturing sector as a whole can be represented by a single production function.

The R&D sector may be analysed according to two specifications: the first refers to that used in section 2.3.3., while the second uses the same production function of the manufacturing sector. In the first case, the output of R&D (the designs for new capital goods) is a function of human capital and the stock of knowledge. The specification is therefore given by

[19] This is equivalent to assume that $\mu=1$ in equation (2.59) which concerns the same model in a closed economy.

$$(2.110) \quad \dot{A} = \delta H A$$

where H is human capital, A is knowledge incorporated in the existing stock of designs and δ reflects the productivity of human capital.

In the second case, the adopted specification implies that the R&D sector uses the same inputs as the manufacturing sector. The production function may thus be defined by

$$(2.111) \quad \dot{A} = \Omega H^{\alpha} L^{\beta} \int_{0}^{A} x(i)^{1-\alpha-\beta} di$$

This specification may be defined lab-equipment, since capital goods are themselves inputs of the innovative process. The first case may be defined as a knowledge-driven specification, since the input of the innovative process are just the stock of knowledge and human capital.

However, it is worth considering the different implications of these two specifications with respect to the benchmark model. In the first case, the model maintains a two-sector structure, as the production possibilities frontier, defined in the design-goods space, maintains the usual concave shape. In the second case, since the production functions in the manufacturing and research sectors are the same, with the exclusion of parameter Ω (scale factor), the production possibilities frontier is a straight line. Therefore, the price of a design (patent) may be determined from the two production functions, and corresponds to the slope of the production possibilities frontier, i.e., $1/\Omega$. In this case the two sectors which compose the economy may be aggregated into a single sector, as in the traditional neo-classic model. The value of output is thus given by

$$(2.112)\quad C+\dot{K}+\frac{\dot{A}}{\Omega}=H^{\alpha}L^{\beta}\int_{0}^{A}x(i)^{1-\alpha-\beta}di$$

As in the model analysed in section 2.3.3., all capital goods are used at the same level, implying that we have $x(i)=x(j)=x^{*}$. The aggregate stock of capital assumes the value

$$(2.113)\quad K=Ax^{*}$$

Equation [2.112] may be rewritten in its reduced form

$$(2.114)\quad C+\dot{K}+\frac{\dot{A}}{\Omega}=H^{\alpha}L^{\beta}A\left(\frac{K}{A}\right)^{1-\alpha-\beta}=H^{\alpha}L^{\beta}K^{1-\alpha-\beta}A^{\alpha+\beta}$$

The market equilibrium which is determined according to the two different specifications of the research sector implies two different ways through which the equilibrium is reached. In the first case, the production function of the R&D sector is homogeneous of degree two. This means that it is impossible for both inputs (H and A) to be paid according to their marginal productivity. It is then assumed that A does not receive any compensation, i.e., it is assumed that the knowledge incorporated in the previously invented stock of designs is fully available and usable by each single individual in the research sector. The equilibrium which is determined is therefore an equilibrium with external effects in the research sector. In this case R&D may be described as an activity undertaken by single researchers, who use their human capital and the available stock of knowledge (not remunerated) to produce new designs from which they obtain a patent.

In the lab-equipment specification the output of the research sector is homogeneous of degree one, as in the manufacturing sector. The equilibrium in this specification is such that there are no external effects and no restrictions on the entrance into the manufacturing and research sectors. The R&D activity may be thought of as an activity performed by identical firms which sell designs for a price P_A determined by the slope of the production possibilities frontier.

2.5.1 The Determination of the Growth Rate

As in the R&D model of a closed economy, the balanced growth rate is determined assuming that the labour force is constant (L and H do not vary). Output dynamics therefore depend on the evolution of K and A. The balanced growth rate may be defined on the basis of two linear restrictions between the growth rate and the prevalent interest rate along the balanced growth path. These conditions are derived on the demand side, from the endogenisation of preferences according to the usual utility function $U = \frac{c^{1-\sigma}}{1-\sigma}$ and, on the supply side, by equilibrium in production[20].

Assuming that the R&D activity is of the knowledge-driven type, the balanced growth rate is given by

$$(2.115)\quad \gamma^* = \frac{\delta H - \Delta_1 \rho}{\Delta_1 \sigma + 1}$$

$$\text{where}\quad \Delta_1 = \frac{\alpha}{(\alpha+\beta)(1-\alpha-\beta)}$$

In the lab-equipment specification the growth rate is given by

$$(2.116)\quad \gamma = \frac{\Delta_2 H^{\alpha} L^{\beta} - \rho}{\sigma}$$

[20] The determination of the balanced growth rate is identical to that described in section 2.3.3. From the intertemporal maximisation of preferences the interest rate is endogenised and defined by: $r = \sigma \frac{\dot{C}}{C} + \rho$

where $\Delta_2 = \Omega^{\alpha+\beta}(\alpha+\beta)^{\alpha+\beta}(1-\alpha-\beta)^{2-\alpha-\beta}$

The determination of the balanced growth rate in the two hypotheses is represented in Figures 2.7 and 2.8.

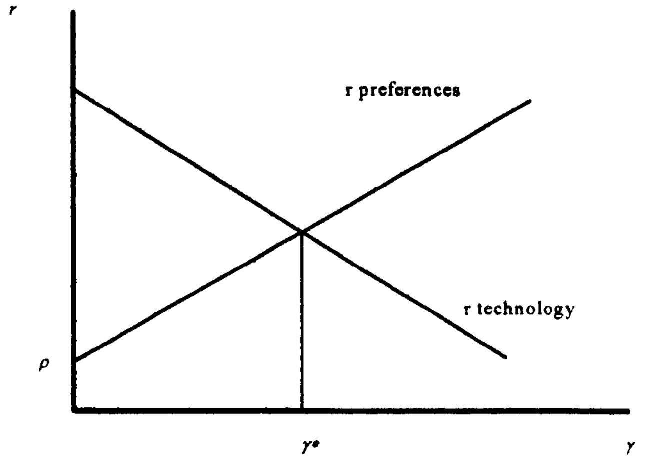

Figure 2.7 *Interest rate and balanced growth rate in the knowledge-driven model.*

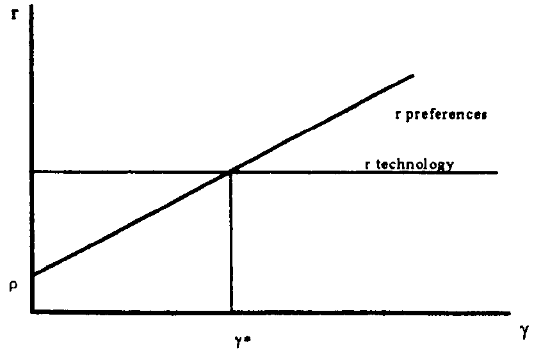

Figure 2.8 *Interest rate and balanced growth rate in the lab-equipment model*

Both these specifications show how the balanced growth rate depends on the size of the economy (scale effect). To show this effect it is sufficient to consider the simple case of two economies which are endowed with the same level of unskilled labour and human capital *(H)*. If we assume that these economies are completely integrated, this means that the stock of human capital and unskilled labour now becomes $2H$ and $2L$ respectively. Both the interest rate and the growth rate increase in both specifications, due to economic integration. It is now worth comparing these effects with those derived from a liberalisation of the flow of goods and knowledge between different countries.

To consider the effects of the flow of knowledge and goods, we deal with a simplified case of two countries with the same amount of human capital (H) and unskilled labour (L); assume that the flows of goods is completely separable from the flows of knowledge. Since final output refers to a single good, it is implicit that the flow of goods concerns only intermediate goods.

Given this hypothesis it is possible to identify the different effects in the two R&D specifications. We consider the following cases:

a) liberalisation of flow of goods without knowledge flow.

This hypothesis leads to two opposite effects. In the knowledge-driven R&D model there are no effects on the balanced growth rate. In fact, along the balanced growth path, the output growth rate is equal to the growth rate of the stock of knowledge

$$(2.117) \quad \frac{\dot{A}}{A} = \delta H_a$$

We have seen that the stock of human capital used in the research sector (H_a) is endogenously determined by the allocation of human capital in the manufacturing sector.[21]

This allocation is determined by the equilibrium conditions of the labour market, i.e., the equality of returns to human capital in R&D and manufacturing. The greater availability of intermediate goods, deriving from trade, does not modify relative remuneration in the two sectors, thus leaving the level of human capital in the research sector (H_a) unchanged.

From equation [2.108] it may be noted that by indicating the stock of intermediate goods available from abroad as A^*, the marginal productivity of human capital used in manufacturing is

$$(2.118) \quad \frac{\partial Y}{\partial H} = \alpha H^{\alpha-1} L^{\beta} (x^*)^{1-\alpha-\beta} (A + A^*)$$

In other words, widening the availability of intermediate goods produces an increase in the marginal productivity of human capital and therefore an equal variation in its remuneration.

The remuneration of human capital in the research sector is also affected by the wider availability of goods. In fact, in this case the market for each new invented good becomes double than the initial one. The price for a patent paid to each researcher is now double the initial price.

In the specification of the model with lab-equipment R&D, there is the opposite effect. The mechanisms which generate a higher growth rate in this case depends on the effect caused by the variation of the interest rate. The value of a patent is constant and determined on the technology side (slope of the production possibilities frontier, $1/\Omega$). However, with a wider market, the price of a patent should rise for a given interest rate.

[21] As in the model of section 2.3.3 the aggregate stock of human capital (H) is divided between the research sector (H_a) and the manufacturing sector (H_a).

The final result is the same as that obtained in the case of complete integration, with a rise, therefore, in the growth rate.

b) liberalisation of knowledge flows

Under this hypothesis, in the knowledge-driven R&D model a permanent increase in the growth rate is obtained.

Consider again the case of two identical countries. The stock of knowledge available to each country becomes $(A + A^*)$ and the growth rate of the stock of knowledge will be equal to $2\delta H_a$. The increase in the stock of knowledge determines an increase in the productivity of human capital used in research. The balanced growth rate now becomes

$$(2.119) \quad \gamma^* = \frac{(2\delta H - \Delta_1 \rho)}{(\rho \Delta_1 + 1)}$$

In this case the same result is obtained doubling the value of H. This has exactly the same effect as a complete integration of the two economies. We may therefore summarise the results as follows:

i) the exploitation of the increasing returns in the equation which defines the production of knowledge is crucial for obtaining a positive effect in economic integration;

ii) the analysis has only considered a hypothesis of countries with the same initial endowments of resources in the manufacturing and research sectors. However, it is not difficult to relax this hypothesis. Grossman and Helpman (1991b) show how the trade between countries with different initial endowments implies a movement of resources between the manufacturing and research sectors which may cause either an increase or a decrease in the growth rate of the economies globally considered. The previous analysis, therefore, is more appropriate if applied to countries with a relatively homogeneous economic structure.

The effects of knowledge diffusion are the same in the model in paragraph 2.3.4. (expansion of product varieties). In this case, the liberalisation of knowledge flow produces a faster accumulation of knowledge and a reduction in the R&D costs in each country. Firms introduce new varieties of products into the market, thus increasing the growth rate.

2.6 Critical Evaluation of Endogenous Growth Theory

In this section we analyse the main drawbacks of endogenous growth models on both theoretical and empirical grounds. We particularly focus on five aspects of endogenous growth models, which in our opinion reflect the main points of controversy:

i) scale effects;

ii) the treatment of knowledge as a production input;

iii) the role of institutions;

iv) the empirical controversy dealing with the robustness of growth regression estimates and the measurement of the impact of some crucial variables (e.g., in vestment) on growth;

v) the simplified representation of R&D;

vi) the absence of any discussion of diffusion phenomena.

i) In the previous sections we underlined that one of the typical results of endogenous growth models is the scale effect, which implies that economies endowed with a large labour force or human capital stock grow faster than less endowed economies. In chapter 4 we shall analyse a modification of the model presented in the previous sections, which allows for knowledge diffusion and thus allows for endogenous growth without scale effects.

In this section, however, we discuss the empirical implication of scale effects derived from R&D endogenous growth models. Following the conclusions of such models, one would expect the growth rate to be a positive and increasing function of the resources devoted to knowledge accumulation (e.g. R&D resources). However, looking at the time series of the growth rate and the resources devoted to R&D (e.g. scientists and engineers) for a large set of industrialised countries, there is not the strong and positive relationship between the two series, that would be expected from the theoretical models. Indeed, resources engaged in R&D show a positive trend, while the growth rate is a stationary time series. Jones (1995a, 1995b) uses this simple argument to support a more general critique of R&D models of growth, suggesting that there is evidence of decreasing returns in the production of new innovation, for it is harder to extend the stock of knowledge once a large stock of knowledge has already been accumulated.

Following Jones, it is then possible to reconcile this empirical evidence with the theory only by allowing for decreasing returns in the production function which defines the R&D sector. The implications of this new specification, however, contrast with the conclusions of previous R&D based models, in that the growth rate is now independent of capital accumulation and of the stock of resources devoted to R&D. However it reconciles the R&D models with the joint time series evidence on R&D and output growth for advanced OECD economies.

This new specification, although important on theoretical and empirical grounds, implies that the long run growth rate is independent of any policy action, as in the exogenous Solow growth model, for the growth rate becomes proportional to the rate of population growth, with the coefficient of proportionality being determined by the parameters which define the knowledge production function.

Jones's argument may be summarised by reconsidering a modification of the Romer model described in section (2.3.3). Final output is described by

$$(2.6.1)\quad Y = K^{\alpha}(AH_y)^{1-\alpha}$$

where K is the aggregate stock of capital, H_y is human capital allocated to manufacturing and A is the aggregate stock of knowledge, whose growth rate was supposed (in the Romer model) to be proportional to human capital devoted to research (H_a), namely:

$$(2.6.2)\quad \frac{\dot{A}}{A} = \delta H_a$$

Jones argues that the empirical evidence calls for a model with decreasing returns in the research sector, implying that

$$(2.6.3)\quad \frac{\dot{A}}{A} = \delta H_a^{\lambda} A^{\gamma-1}$$

with γ being strictly less than 1, and $\lambda \leq 1$. Thus, the R&D sector is now described by a production function which shows decreasing returns to the factor used to proxy the total stock of knowledge (A).

Jones shows that under this new hypothesis the long run growth rate becomes proportional to the rate of population growth :

$$(2.6.4)\quad g = \frac{\lambda n}{1-\gamma}$$

where g is the long-run growth rate of the economy, n is the population growth rate, and λ and γ are the parameters which define the knowledge production function.

Jones argues that the input to R&D, as proxied by the number of scientists and engineers engaged in R&D, has risen dramatically over the last decades, while leaving the growth rate of the economy steady. Jones uses this argument to conclude that in order to reconcile the R&D endogenous growth models with the time series evidence for the advanced OECD economies, it is necessary to allow for decreasing returns in research activity, thus eliminating the dependence of the long-run growth rate on policy.

However, this conclusion may be criticised by arguing that the correct prediction would be that the fraction of GDP allocated to R&D be constant, instead of predicting that the number of scientists and engineers engaged in R&D be constant during a period of relatively steady growth. Looking at the time series evidence for the ratio of R&D to GDP and the growth rate of GDP per-capita for the US economy since the 1950s, one can argue that this evidence is consistent with endogenous growth theory, and does not contradict it, as suggested by Aghion and Howitt (1996).

Moreover, any analysis of this debate should take into account other drawbacks typical of all R&D endogenous growth models, which we now point out.

ii) In R&D endogenous growth models knowledge is considered as similar to any other production input, such as labour or capital. In reality, the growth of knowledge takes the form of new ideas, thus posing a crucial problem of aggregation. In the models analysed in the previous sections, the aggregate stock of knowledge is proxied by the number of invented goods (A). This measure is based on the assumption of a one-to-one correspondence between ideas and new capital goods, thus ignoring the aggregation problem that arises when new capital goods are of different qualities.

In addition to this theoretical problem, there is also a measurement problem which arises on empirical grounds but is common to the general empirical literature on growth. Following Howitt (1996) we can identity three major problems when measuring knowledge-based growth:

a) a "knowledge-input problem";

b) a "quality improvement problem";

c) an "obsolescence problem".

The first problem derives from the underestimation of knowledge input using standard measure of R&D and information sector resources, as this estimation rules out many of the informal activities undertaken by firms or workers to produce knowledge associated with either a new product (or process) or new organisational structures.

In addition one should note that not all advances in the state of scientific knowledge come about from organised R&D activities. Technical improvements may also occur as a by-product of other activities or from non domestic soureces (i.e., imports of capital goods). Many innovations are applied imperfectly when first introduced and are therefore improved gradually over time as a result of experience. This gradual improvement can be seen as an intrinsic part of the innovation process, running from research through development to production and then to improved production. Thus, scope for improvement may be discovered as a result of a learning process and not as a result of formal R&D activity.

The second problems arises as R&D results in new and qualitatively better goods. In this case the effects on output growth can be underestimated because of the difficulties in constructing price indexes incorporating quality changes. Some of the R&D based models do consider quality improvements on theoretical grounds (and we have underlined the aggregation problem), but their implications cannot easily be tested because of this problem.

The third issue reflects a sort of "obsolescence problem" , because the aggregate stock of knowledge depreciates as new discoveries and innovations take place. Moreover, one should also consider that the creation of knowledge causes the depreciation of existing physical and human capital. This is particularly significant when there is a new wave of innovations, which accelerates depreciation of both the existing stock of knowledge and other production inputs.

iii) The role of institutions is understated, and this rules out one important element of the growth process which affected the industrialised countries during the last century. North (1989) pointed out that most of the growth in productivity which has occurred since the beginning of the industrial revolution is attributable to institutions which have permitted the exploitation of intellectual property rights and the reduction of transaction costs.

iv) The empirical controversy deals with many substantial econometric problems, which we summarise briefly. However, these problems typically underlie the lack of adequate proxies for the effects one wants to estimate and therefore also the lack of an adequate set of variables which can be used to solve structural growth models.

We can identify, among others, three main problems affecting growth regressions.

The first is that cross-country estimates implicitly assume that the parameters of the underlying production function are the same for all countries, if necessary taking into account the different initial conditions by means of deterministic fixed effects. In their seminal paper on sensitivity analysis, Levine and Renelt (1992) pointed out that problems of parameter heterogeneity are a crucial drawback to growth regressions, as the underlying estimates may be inconsistent.

The second problem deals with the endogeneity of some of the variables used in growth regressions. One typical example is investment in physical or human capital, which is taken either as exogenous or instrumented in ways which are not satisfactory. The lack of an adequate set of explanatory variables excludes the use of simultaneous models, which could represent a significant improvement within the empirical literature.

Thus it becomes important to analyse the possible causal links between the variables used in growth regressions, in order to specify the empirical model correctly. This is a crucial issue, which we shall discuss in detail in chapter 5 and 6.

The third problem concerns cross-section regressions involving a large number of countries, some of which may be unrepresentative, because of measurement errors or parameter heterogeneity. These observations may affect the coefficient estimates and their precision, if they are influential outliers. This problem typically arises when the cross-section of data includes underdeveloped countries for which measurement errors becomes a crucial issue. An illustration of this is given by the debate on the effect of investment on growth in the context of underdeveloped countries. De Long and Summer (1992a) underline that the presence of outliers in their data set (e.g. Botswana) implies estimated coefficients for the equipment investment share which may be almost 50% bigger than in the case of outlier exclusion. Consequently the goodness of fit may also be affected, as adjusted R^2 may vary between 0.29 and 0.21 depending on the inclusion (exclusion) of such countries. Auerbach, Hassett and Oliner (1994) use these findings to criticise De Long and Summers' conclusions in more detail, thus raising doubts as to the robustness of their empirical investigation.

This latter point leads us to the discussion of another point of controversy, which is still a central issue in the empirical debate, namely the measurement of the impact of investment in the growth process.

The role of fixed investment, particularly the machinery and equipment component, is probably overestimated by new growth theory. We shall analyse this issue in more detail in Chapter 7 by testing the causal relationship between growth and investment.

Here we want to underline that endogenous growth theory, particularly the so-called AK models, emphasise the role of capital accumulation in the growth process, suggesting that a modification of the rate of capital accumulation has significant long-run growth effects. This conclusion leads to important implications for economic policy, as incentives to capital accumulation may have long-run growth effects. However, the empirical evidence is controversial. On historical grounds, it is true that the richer and more developed countries are those that were first in inventing and applying capital intensive technologies, with new equipment embodying the most advanced technological knowledge.

In their empirical investigation, De long and Summers (1992a, 1992b) find that machinery and equipment investment accounts for a substantial part of the variation in the rates of growth of per capita income in a large cross-section of countries over a time interval of almost 25 years. This result is consistent with different specifications of the empirical model which allow one to control for other factors affecting growth. Thus they conclude that machinery and equipment investment does have a clear long-run effect on output growth. However, this evidence must be also supported by time series investigations, which are the methodological requirement for establishing the dynamic impact of machinery and equipment investment on output growth. In addition to the previously mentioned problem of outliers, their estimates perform better in the context of developing countries, while within the OECD countries the role of machinery and equipment investment is less significant and strong. In Chapter 7 we contribute to this debate, using a time series perspective and looking at the causal link between growth and investment.

v) The endogenous growth models described in the previous sections can also be criticised for their simplified representation of R&D activities. Any such activity is carried out by a single agent who is simultaneously the financier, creator, owner and user of the innovation.

In reality, R&D activity takes place either within firms where there are structured research department, or through contractual agreement between firms. In any case, the financing decision, the allocation of resources among the departments, the use of the innovation and the sharing of property rights are more complex than the aggregate representation of R&D based models suggests.

The description of the research sector and particularly the management of R&D activities could be enriched by using the developments of the theory of organisations and the theory of contracts (Teece (1988), Grossman and Hart 1986). In this framework one could consider the contractual relationship between researchers and customers, i.e., all parties directly benefiting from the innovation. Within the R&D endogenous growth models, this implies considering the kind of contractual relationship between researchers and firms in the manufacturing sector which use the innovations from the research sector to produce final goods. One should therefore specify the allocation of property rights for any innovation and a sharing rule on the revenue obtained by researchers.

Another crucial problem which is typical of all research activities (and which is not well specified in the endogenous growth literature) is financing. Although private internal financing is the most important source for high-tech firms' R&D in most of the industrialised countries, private outsider or public financing is still a crucial component of the overall resources dedicated to R&D.

Private outsiders are essentially banks, and in countries like the US or UK where financial markets are more developed they can take the form of venture capital, typically devoted to start-up initiatives of high-tech firms.

Government intervention is crucial too, and takes the form of subsidies to R&D or direct investment in specified R&D projects, particularly oriented towards specific sectors (e.g. aerospace and the military industries). R&D endogenous growth models do consider government intervention. However, this analysis is often confined to a quantitative view, namely what is the optimal subsidy to R&D investment or the optimal taxation needed to reach an optimal allocation of resources.

As we pointed out before, R&D activities can also be regulated by formalised contracts between two parties: researchers and the parties that directly benefit from the research activity. This contractual relationship can be modelled using the principal agent literature, which highlights the typical agency problem with incentive constraints. In this framework, government intervention to support R&D can take the form of different contractual enforcement activities.

All the issues raised so far, while giving a more realistic representation of the research sector than that otherwise described in the R&D endogenous growth models, complicate the theoretical structure of such models and therefore represent an open future research program within the endogenous growth literature.

vi) endogenous growth models do not explicitly consider technological diffusion, thus ignoring one crucial element of technological change. This issue will be analysed in Chapter 4, where a new model incorporating the diffusion process will be described.

2.7 Conclusions

The neo-classical growth model and the approach suggested by the endogenous growth theory have been critically analysed. New growth theory analyses the key factors which may determine technological progress and therefore affect the long-run growth rate of the economy.

Three main research directions have been followed, refining hypothesis advanced in the sixties. We find models which follow the learning by doing hypothesis and therefore consider knowledge embodied in physical capital. The second class of models incorporate knowledge within human capital while the third approach considers knowledge as generated by the research sector which sells designs to the manufacturing sector producing capital goods.

A typical outcome of these models is the existence of externalities which causes divergence between the market and socially optimal equilibria. Policy intervention aimed at subsidising either human capital or physical capital find, therefore, a justification.

Another typical outcome of these models is that the growth rate is positively affected by the size of the economy (scale effect). As we will see in the third chapter, this result is not confirmed by empirical evidence and does not hold if one introduces new hypotheses (e.g. knowledge or technological diffusion).

The empirical analysis received new impetus from the increasing theoretical debate. However, the empirical tests are mainly based on heterogeneous cross section data which take into account mean growth rates over given periods of time, thus avoiding pure time series analysis.

On empirical grounds, the role of investment in the growth process has been emphasised. This variable has also been decomposed to consider the impact of machinery and equipment investment alone.

In the sixth and seventh chapters we will discuss this issue focusing on the possible causality links between output growth, investment and innovative activity.

Another empirical test which follows the theoretical models discussed in this chapter is the so-called convergence hypothesis. It has been underlined that absolute convergence can only be found in relatively homogeneous economies, e.g., the United States, while conditional convergence prevails in cross-country analysis.

Endogenous growth models may also be extended to an open economy framework, to show the effects of the flow of knowledge and goods on growth. The results still show a scale effect on growth and crucially depend on the hypotheses of the characterisation of the production function in the R&D sector.

CHAPTER III

3. The Economics of Technological Diffusion

3.1 Introduction

In the second chapter we analysed endogenous growth models emphasising sources of innovation and hence of growth. The innovative process in these models is instantaneous, thus ignoring diffusion, which is, however, a crucial component of the whole innovation process.

Indeed, innovation requires time to be fully utilised by the entire economy. According to the Schumpeterian taxonomy, technological change may be broken down into three stages: invention, innovation and diffusion. The innovative stage, i.e., the generation of new technologies, is very often taken to encompass the entire process of technological change, ignoring the fact that new technologies are not instantaneously used by all potential adopters. The growth models analysed so far implicitly consider an instantaneous diffusion of innovations. This assumption, although it simplifies the analytical structure of these models, leads to unsatisfactory results. An example is scale effect which is a typical result of the analysed models. As we describe in the next chapter, this effect no longer holds if we assume a non-instantaneous propagation of knowledge.

Another example is given by the possible impact of capital production costs on the growth rate. Assuming a non instantaneous use of new intermediate goods, the growth rate is affected by the parameters which define the diffusion process and in turn determine capital production costs.

The aim of our investigation is to bridge the gap between two theoretical approaches dealing, on the one hand, with the determinants of growth and, on the other, with the theory of technological diffusion. In this chapter we focus on the theoretical analysis of technological diffusion; we shall then analyse the interactions with the new growth theory in the next chapter.

A stylised fact of the theoretical and empirical literature on diffusion concerns the non-monotonic path of the diffusion process, which leads to an "*S*" shaped time path typically represented through a logistic function.

The literature has generally made a distinction between intra-firm diffusion and inter-firm diffusion. The former deals with the analysis of diffusion within a single firm, while the latter analyses the change in the number of adopters within an industry. The analytical approach used to investigate both classifications is similar and in this chapter we refer solely to inter-firm diffusion.

The analysis is organised considering first demand based models and then information and uncertainty issues within the decision adoption process. In addition, we analyse in depth the so-called integrated models, which provide an exhaustive approach to the diffusion process and a better integration with the growth models of the previous chapter.

3.2 Demand-Based Models

In this section we analyse those approaches which consider the diffusion of new technologies as determined mainly by demand factors. The analysis first considers the so-called probit models and models with strategic interactions. These approaches assume the absence of imperfections in the acquisition of information by firms.

3.2.1 Probit Models

This approach considers firms' characteristics and predicts the adoption of new technologies according to the distribution of these characteristics. In David (1969) each firm may be identified by a certain characteristic (C), which is distributed among the population of firms according to a given density function $f(C)$ with cumulative distribution $F(C)$. Firm size is the typical characteristic (C) which is considered, and figure 3.1 shows a hypothetical distribution. C^0 is the critical value of C, i.e., the threshold value below which the introduction of innovation is not profitable.

A potential user (j) of the new technology will be an effective user of the innovation if its critical value is such that $C_j > C^0$. Assuming that as time proceeds either distribution $f(C)$, or the critical value C^0 change, the number of firms using the new technology increases and the diffusion process is thus generated. From the cumulative distribution function $F(C)$ it is possible to determine the proportion of firms which will have adopted the new technology at time t, i.e., $1 - F(C)$. In terms of figure 3.1 this proportion is given by the shaded area.

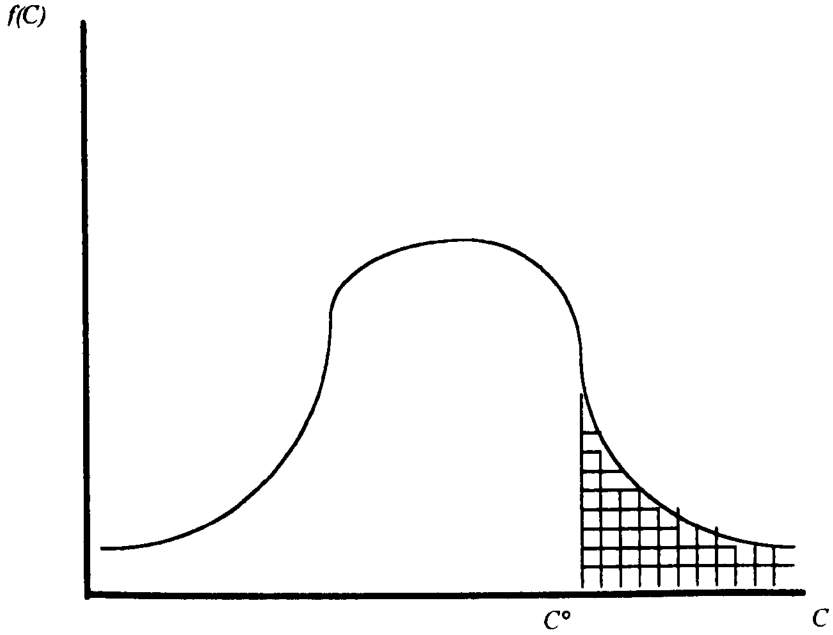

Figure 3.1

The previous definition of C^0 must be clarified, to understand how the diffusion process is generated in these models. In David (1969) the critical firm size is defined as that output level at which the increase in capital costs caused by the acquisition of the new technology is compensated by a reduction in labour costs. Other models, in particular Davies (1979), discuss these issues within the same framework. The Davies model suggests that potential users of the new technology will adopt if initial cost of innovation is expected to be paid off within a given pay-off time. However, one must take into account that firms in an industry differ with respect to:

i) their knowledge and their ability to understand the information related to the new production technique;

ii) their attitude towards risk;

iii) their objectives.

The different behaviour of firms may be proxied by their different sizes. Both on theoretical and empirical grounds it is possible to figure out a positive relationship between the probability of adoption and firm size. In both the David and Davies models large firms are the first users of new technology, and diffusion proceeds following the size distribution of firms. Nevertheless, only the Davies model has been extensively tested, showing that the positive relationship between firm size and adoption is supported.

This analytical approach can be criticised on different grounds, as diffusion is substantially determined by exogenous factors such as the change in relative prices of inputs and learning and expectations are not taken into account These aspects are analysed in greater detail in the following sections, particularly in integrated models that jointly consider demand and supply issues .

3.2.2 Uncertainty, Information and Learning

The diffusion of new technologies is a process which takes place in an environment characterised by imperfect information and, therefore, by uncertainty. The models which originally analysed these issues are the so-called epidemic models. The main hypothesis of this approach lies in the assumption that information is acquired by potential users of new technology through direct contact with other innovative entrepreneurs (past users). The acquisition of information through other sources, internal or external to the firm, is therefore often excluded. This simple hypothesis leads to a time path of diffusion which is logistic, and the diffusion speed depends on the frequency of contact between entrepreneurs.

This approach has been criticised for assuming homogeneity of potential users, an absence of technological improvement, and too simple treatment of information acquisition. A variant of the basic hypothesis has been developed by Lekval and Wahlbin (1973), where information may also be acquired from sources external to the group of firms which have already adopted the new technology. Lekvall and Wahlbin show that, in this case, the diffusion curve is no longer logistic. A version of the epidemic model which, particularly on empirical grounds, has been widely applied, is that proposed by Mansfield (1968) in which the diffusion speed is determined by the expected profitability of innovation, firm size, the risk associated with innovation and the number of potential adopters. Despite the success of this model, much criticism has been made of it, focusing on some crucial assumptions such as the constancy of profitability and the decreasing pattern of uncertainty.

These problems were only faced later, in particular by Stoneman (1980, 1981) and Jensen (1982). In the version presented by Stoneman, information derives entirely from internal sources and the use of the new technique depends on:

i) the mean and variance of returns associated with new technology;

ii) the mean and variance of returns associated with old technology;

iii) the initial estimate of the mean and variance of returns associated with new technology;

iv) attitudes towards risk;

v) the correlation between returns on new and old technology.

Tonks (1983) includes in this model the acquisition of information through external sources, thus giving a value (price) to information. This generates a situation where firms, instead of waiting for the arrival of information, search for it. Jensen (1982) considers the problem of a firm which receives information from external sources including a learning process. The firm adopts a Bayesian criteria in updating the set of information and at any time it may decide to acquire or not acquire information or wait for further information. It must be underlined that the decision to adopt the innovation is considered irreversible and firms are risk neutral. Under the usual profit maximisation hypothesis, the firm's problem is to determine the time at which the acquisition of information should be stopped (the stopping problem). The optimal behaviour of the firm is determined, according to this model, by the adoption of new technology when expected profitability exceeds a given threshold level.

3.2.3 Models With Strategic Interactions

The diffusion path may be also derived within a strategic framework. This approach recalls previous Schumpterian analysis, according to which an innovation introduced by a firm increases profit expectations and therefore pushes other entrepreneurs (imitators) to enter the market. The reduction of the cost of the innovation observed over time further encourages the entrance of new firms, thus generating the diffusion path.

In some of the models with strategic interactions the reduction of the costs associated with innovation is the key factor which determines diffusion. In Reinganum (1981a, 1981b, 1983), strategic competition among firms relates to the choice of the time of innovation, assuming that adoption costs decrease through time and that the profits gained for introducing the new technology decrease when the number of firms which adopt it increases. In this framework firms have perfect information and the market equilibrium, which results from an oligopolistic non-cooperative game, implies sequential adoption by firms.

3.3 The Integrated Approach

The models analysed so far have considered only the demand side in the diffusion process. However, diffusion is the result of interaction between the demand and supply of new technologies. An analysis of the interaction between demand and supply sectors is necessary if one wants to fully understand the determinants of the diffusion process and make this process fully endogenous.

The integrated models generally assume that innovation is produced in one sector and later sold to a firm in the same or another sector. It should be pointed out that the industry which produces new technology makes product innovations, while the demand sector makes process innovation. In the supply sector it is possible to identify as the main determinants of diffusion spread :

i) the evolution of industrial costs;

ii) the output capacity of firms;

iii) the market structure and therefore possible interaction between firms.

A simple illustration of the integrated approach follows the study by Ireland and Stoneman (1986). In this model the industry which supplies new technology is oligopolistic with N firms competing in accordance with the classic Cournot assumptions. Perfect competition and monopoly can be viewed as special cases when $N \to \infty$ or $N \to 1$. Supplying firms are aware of the demand function, which is determined through the probit approach. A crucial assumption concerns the role of learning economies (Arrow (1962), Spence (1981)), which enable production costs to decrease over time. The diffusion path is determined by price reduction, which in turn generates an increasing use among potential users. The price dynamic path is thus crucial for generating the diffusion process. Price expectations may also affect the diffusion path, since there is an incentive for buyers to postpone adoption as prices decrease over time.[1]

We shall analyse this model in more detail, since it represents the bridge between the analysis of technological diffusion and the new growth models. As we have stressed, it is a model in which the demand and supply sides are both considered and we shall first describe the demand side. This is composed of a fixed number *N* of potential users. The decision to purchase depends, as in the traditional probit models, on firms' characteristics (e.g. firm size). We define $f(C)$ as the marginal profit deriving from the adoption of new technology by a firm with characteristic C. We also assume that this increase in profits is perpetual, thus generating a present value of $f(C)/r$, where r is the discount rate. The cost of acquisition of new technology at time t is p_t, while the expected cost at time t+1 is p^e_{t+1}. Given the hypothesis of profit maximisation for the firm with characteristic C, the acquisition of new technology takes place if two conditions are satisfied:

a) the profitability condition:

$$(3.1) \quad \frac{f(C)}{r} \geq p_t$$

[1] See also Rosenberg (1976) for a discussion of the role of expectations with regard to difffusion.

b) the arbitrage condition:

$$(3.2)\quad (1+r)p_t - p^e_{t+1} \leq f(C)$$

Condition 3.2 establishes that it is not profitable to wait for adoption until time $t+1$.

It may be noted that, if the firm has myopic expectations (i.e., $p^e_{t+1} = p_t$), 3.2 collapses to 3.1 and the profitability condition is the condition which determines the use of new technology. On the other hand, if the firm has rational expectations (perfect foresight in absence of uncertainty),

$p^e_{t+1} = p_t$ and $p_{t+1} < p_t$, the satisfaction of 3.2 implies that condition 3.1 holds and thus condition 3.2 generates the use of technology.

If C_t is the characteristic of the marginal user at time t, under the hypothesis of myopia we have:

$$(3.3)\quad f(C_t) = rp_t$$

Since it is assumed that the potential population of users is fixed and equal to N, the number of users at time t, (U_t), is

$$(3.4)\quad U_t = N(1 - F(C_t))$$

From [3.4] we get:

$$(3.5)\quad \frac{N-U_t}{N} = F(C_t)$$

and

$$(3.6)\quad C_t = F^{-1}\left(\frac{N-U_t}{N}\right)$$

Substituting [3.6] in [3.1] yields:

$$(3.7)\quad p_t = \frac{1}{r} f\left[F^{-1}\left(\frac{N-U_t}{N}\right)\right]$$

It is also assumed that each firm buys one unit of the new capital good per unit of time yielding that the capital stock at time t is $K_t = U_t$.. We may therefore write the inverse demand function which relates the price of the capital good at time t to the quantity demanded. We thus have

$$(3.8)\quad p_t = \frac{1}{r} f\left[F^{-1}\left(\frac{N-K_t}{N}\right)\right] \equiv \frac{1}{r} h(K_t)$$

One may also derive the corresponding demand function under an assumption of perfect foresight

$$(3.9)\quad p_t = \frac{f}{1+r}\left[F^{-1}\left(\frac{N-K_t}{N}\right)\right] + p^e_{t+1}$$

and therefore:

$$(3.10)\quad p_t = \frac{1}{1+r}h(K_t) + \frac{p^e_{t+1}}{1+r}$$

Equations [3.8] and [3.10] enable us to define the demand functions under different hypotheses on price expectations.

It is also assumed that the sector which produces intermediate goods is characterised by n identical firms, which maximise their expected profits given the choice of the other (n - 1) firms. Expected profits for a firm in this sector may be described by

$$(3.11)\quad E(\Pi) = \int_0^\infty [p(t) - c(t)]q(t)e^{-rt}dt$$

where p is the price (derived from the demand functions [3.8] or [3.10], q the quantity produced at time t and c the unit cost of production. The discount rate r incorporates the probability that the new product becomes obsolete between time t and $t + dt$[2]

[2] It is possible to define $r=r'+h$ where r' is the discount rate and h is the probability of obsolescence.

It is also assumed that the cost function is decreasing with time, i.e., it is assumed that the firm has learning economies which enabled it to reduce production until a given time, say, t^*. Because of intertemporal profit maximisation, the supply paths of new technology under the two expectation regimes are

$$(3.12)\quad h(K) = rc - \dot{c} + \frac{n-1}{n} Q \frac{h_k}{r}$$

$$(3.13)\quad h(K) = rc - \dot{c} - \frac{h_k K}{n}$$

where the dot sign refers to the derivative with respect to time, h_k is the derivative of h with respect to K and Q is current production of the whole industry. Equations (3.12) and (3.13) show the diffusion path under myopia and perfect foresight respectively and figures 3.2 and 3.3 also plot the cost and diffusion functions under these regimes.

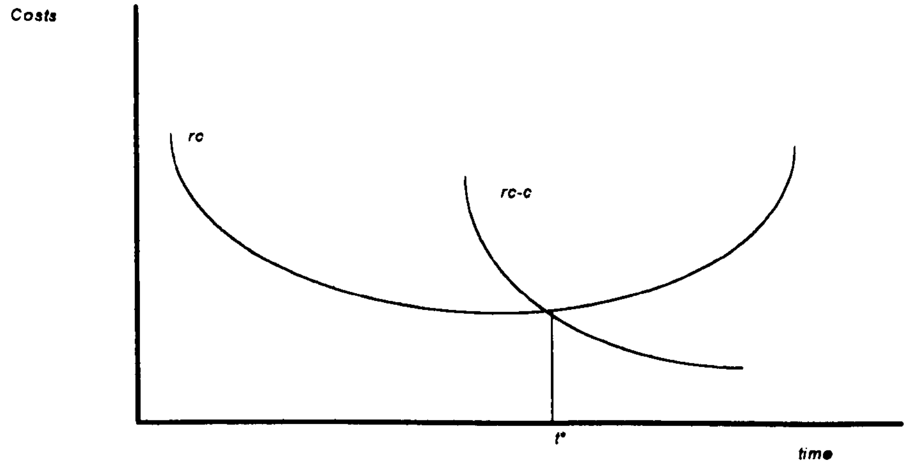

Figure 3.2

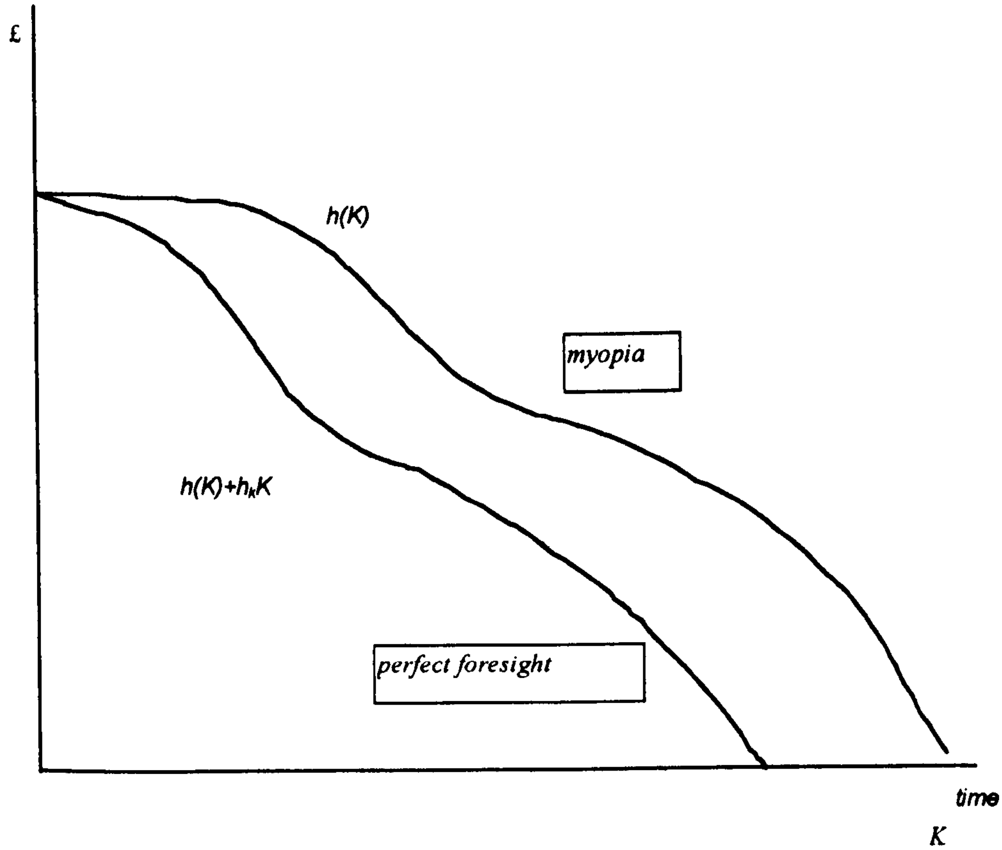

Figure 3.3

For the sake of simplicity we shall consider the case of a single supplier ($n = 1$). Figure 3.2 shows the curves rc and $rc-\dot{c}$. The two curves intersect at t^* where unit production costs reach the minimum. It may be noted that under monopolistic supply, diffusion terminates at time t^* in both expectation regimes. However, the use of technology is lower at any time under the perfect foresight hypothesis. The rationale of this result is that, under perfect foresight, the arbitrage condition 3.2 holds, and this gives an incentive to delay adoption if prices decrease over time. The other cases analysed yield the following conclusions:

i) for a given number of producing firms, diffusion is faster if buyers have rational expectations of technology prices;

ii) given price expectations, when the number of producing firms increases, the spread of diffusion also increases

iii) perfect competition in the supplying sector together with perfect foresight of prices on the demand side involve the same diffusion path that would have been obtained in the case of a single producer and buyers with myopic expectations.

The model has important implications for social welfare, as it does not predict that a higher diffusion speed is always socially optimal. What is optimal crucially depends on the hypothesis on expectations and the cost reductions which affect the characteristics of the diffusion path.

These results are obtained by assuming that the number of producing firms does not change along the diffusion path. This is obviously a strong limitation, which does not reflect the results of some empirical tests (Gort and Klepper 1982). However, the endogenisation of the number of producers still represents a controversial element in the theoretical investigation of technological diffusion.

3.4 Empirical Tests

There is now a considerable empirical literature on the diffusion process. Since the original studies by Griliches (1957) and Mansfield (1968) the aim has always been to estimate the appropriate equation to fit the dynamic path of technology use. The typical estimated functions (logistics, Gompertz, log-logistics) have shown an *S*-shaped diffusion path for different economic sectors, including innovations introduced into the agricultural sector (Griliches 1957). This methodological approach has represented an important stage of empirical investigation of diffusion, but it is not directly linked to any theoretical model. In a recent study, Karshenas and Stoneman (1993) propose an empirical approach which allows one to discriminate between different theoretical hypotheses and identifies the determinants of the diffusion process.

The effects which summarize the different theoretical approaches to diffusion may be listed as follows:

a) *rank effect.* This effect is based on the assumption that potential users of new technology get different returns, depending on their intrinsic differences (e.g. firm size). This allows one to specify a distribution of reservation prices among potential users. Thus diffusion proceeds as production costs decrease over time, and firms adopt the new technology as long as prices fall below their reservation price. This literature refers to the so-called probit models and, within the integrated models, to the model proposed in Ireland and Stoneman (1986);

b) *stock effect.* When the use of new technology increases and production costs fall, prices tends to fall and output expands, thus affecting expected profits derived from the use of new technology. Furthermore, assuming that the increase in use decreases expected profits, there will be a number of potential users for whom use will not be profitable for a given cost of acquisition. A diffusion path can be generated by progressive reductions of acquisition costs (Reinganum 1981);

c) *order effect.* This is an extension of the stock effect, through which higher profitability is attributed to higher order users of new technology (Fudenberg and Tirole 1985; Ireland and Stoneman 1985). A firm decides the time of acquisition by taking into account the cost of new technology and the number of previous users, with acquisition cost reductions generating the diffusion process;

d) *epidemic and information effecs.* According to these approaches the diffusion of new technologies takes place through the acquisition of information, typically according to Bayesian rules (Stoneman 1981) or through direct contact among innovative firms (epidemic models) (Mansfield 1968).

The empirical tests proposed by Karshenas and Stoneman on CNC innovation in the UK engineering sectors are based on a joint test of the four effects previously described. They show that the rank and epidemic effects significantly explain the diffusion of new technologies, while the stock and order effects, reflecting the so-called game strategic approach, are not significant.

3.5 Technological Diffusion at Economy-Wide Level

In this section we consider those approaches which analyse the diffusion of new technologies at the economy-wide level. We concentrate on two main lines of research:

a) vintage models;

b) stock adjustment models.

3.5.1 Vintage Models

Vintage models deal with exogenous technological innovations incorporated in new capital goods which, once used in the production process, substitute for old capital goods. Different degrees of substitution among production inputs may be considered before and after the adoption of new technology. One typical example in the literature is the case of a flexible before and a fixed capital-labour ratio after the installation of the new capital good (putty-clay hypothesis). At each point in time the capital stock of the economy is composed of goods of different ages with different production capacities. Each new investment is composed of plants and machinery of the latest vintage. The oldest machine in production just covers its operating costs. Plant which does not cover these costs is scrapped from the production process. A simplified economy embodying technical progress may be represented as follows[3]:

$$(3.14)\quad Y(t,v) = L(t,v)^{1-\alpha}\, Be^{g_a v} K(t,v)^{\alpha}$$

where $Y(t,\ v)$ is production at time t obtained with plant of vintage v; $L(t,\ v)$ and $K(t,\ v)$ are respectively the labour force used and the capital stock of vintage v at time t.

The term $Be^{g_a v}$ is an index of embodied technical progress. The oldest machines are less productive and the rate of growth of productivity of the new machines is given by the parameter g_a. Aggregate output may be represented by

[3] See Solow (1960) and Salter(1966).

$$(3.15)\quad Y(t) = \int_{-\infty}^{t} Y(t,v)dv$$

Using the same methodology, one may define the total employed labour force as

$$(3.16)\quad L(t) = \int_{-\infty}^{t} L(t,v)dv$$

The capital stock of vintage v at time $v, K(v, v)$ is defined as the sum of new investment and substitution investment

$$(3.17)\quad K(v,v) = I(v) + D(v)$$

where $D(v)$ is the level of the substitution investment.

Aggregate capital stock is given by

$$(3.18)\quad K(t,v) = I(\tau)e^{-\lambda(t-v)}$$

where λ is the capital depreciation rate[4].

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[4] This relationship is obtained assuming that the number of machines that must be substituted is proportional to the number of those still operative.

Such vintage models are typically used under the traditional neo-classic hypothesis of competitive markets. Following this hypothesis, prices may then be determined at each point in time. It is worth considering how an economy characterised by the production function [3.14] reacts to the appearance of new technology. Initially markets are in equilibrium and there is full employment, and savings and investment are equal. Moreover, capital stock is made up of several vintages, the oldest of which has an operating cost equal to output price. New technology is superior to previous technology at current prices and thus a new production capacity is created. This causes an increase in the demand for labour, which in turn involves a rise in wages. The equilibrium between investment and savings will be such that no extra profits will be gained for given wages and rental costs. The output price decreases as production increases, involving a substitution of that plant whose operating costs are higher than its output price. At each point in time there is, however, an improvement in technology which causes an increase in the use of that technology. The vintage models show how it may be rational for a firm to use old technology, even if new solution exists. Old machines may contribute to the total profitability of a firm as long as the price of output covers operating costs. Only when new technology reduces price below operating costs will old machines be scrapped. One important drawback of the vintage models is worth noting, i.e. their inability to determine a clear diffusion path crucially depending on the age structure of existing capital, improvements in technology and the change in relative prices.

3.5.2 Stock Adjustment Models

In the theory of investment a crucial role is played by the so-called desired level of capital (K^*), which is compared with the actual level K_t . Investment is a certain proportion of the difference between K^* and K_t, since adjustment costs, which are associated with new investment, render the adjustment towards the desired level gradual and not instantaneous. The rationale for adjustment costs may vary. Penrose (1959) mainly concentrates on management costs, while Nickell (1978) justifies them by arguing that as demand for capital goods rises, the price of these goods rises to compensate the growing costs in the sector which produces the capital goods.

However, the approach developed in Nickell enables one to clarify the link with the literature on technological diffusion. To show how it is possible to generate a diffusion process within this approach, one should think of a representative firm at time t which is endowed with capital K_{t-1} . It is assumed that this firm maximises profits by choosing an appropriate capital level (K_t), constrained by the adjustment costs deriving from the divergence between the capital level K_{t-1} and K_t. For sake of simplicity one can assume that the firm expects current prices to be maintained indefinitely, that the choice of K_t does not influence the adjustment costs in future periods, that there is no depreciation and that the labour input is constant and normalised to unity. Thus the production function is defined by

$$(3.19) \quad Y_t = K^{\alpha}{}_t \qquad \alpha>0$$

The profit function is

$$(3.20)\quad \Pi = pY - rK - g(K)$$

where p is the output price, r the cost of capital use and $g(K)$ the adjustment costs. The first order condition for profit maximisation is

$$(3.21)\quad p\frac{\alpha}{K_t} - r = g_k$$

If we define K* as the equilibrium capital stock , i.e. , $K_t{*} = K_{t-1} = K_t$ it must be true that

$$(3.22)\quad \frac{p\alpha}{K_t\,*} = r$$

and

$$(3.23)\quad K_t\,* = \frac{p\alpha}{r}$$

Substituting [3.23] in [3.21] yields:

$$(3.24)\quad p\alpha = \left(\frac{1}{K_t} - \frac{1}{K_t^*}\right) = g_k$$

Assuming that

$$(3.25)\quad g_k = a\left(\frac{1}{K_{t-1}} - \frac{1}{K_t}\right) \quad a>0$$

adjustment costs may take a simplified form to yield:

$$(3.26)\quad \frac{K_t - K_{t-1}}{K_{t-1}} = \frac{p\alpha}{a}\left(1 - \frac{K_t}{K_t^*}\right)$$

Equation [3.26] is the typical differential equation of the logistic curve with a diffusion speed crucially depending on the parameter a, reflecting adjustment costs. The adjustment costs function has the usual properties (Nickell 1978) if $g(K)>0$, $g_k>0$ $g_{kk}>0$, where g_k and g_{kk} denote first and second order derivatives with respect to K.

The functional form adopted for adjustment costs therefore plays a crucial role for the definition of the diffusion path. This analytical approach enables one to identify a clear and important link between the theory of investment and the analysis of technological diffusion. This link will also be crucial when we incorporate the diffusion process into the new endogenous growth models below.

3.6 Conclusions

We have analysed the main theoretical approaches to technological diffusion by focusing on:

i) probit models;

ii) models dealing with information constraints and uncertainty;

iii) models with strategic interaction;

iv) integrated models.

The first type normally considers firm size as the crucial variable affecting diffusion, while in the second approach diffusion is viewed as a problem of information acquisition and choice under uncertainty. In the strategic interaction approach, on the other hand, the time of innovation is dependent on the behaviour of rivals.

We have also described the integrated approach, which explicitly considers demand and supply interaction. This approach also enables one to consider the impact of expectations (regarding prices and technology) on the diffusion path and represents the methodological tool used to introduce diffusion into an endogenous growth model in fourth chapter below.

In addition this approach enables one to reach important considerations on welfare issues e.g. faster diffusion is not always socially optimal. The optimal diffusion path depends on the interaction between demand and supply, on price expectations and on reduction in the cost of producing capital good .

We have also analysed the problem of diffusion at the economy-wide level, focusing on the vintage and stock-adjustment approaches.

CHAPTER IV

4. Output Growth and Endogenous Technological Diffusion

4.1 Introduction

In the previous chapters we have independently considered two issues: economic growth, and the diffusion of new technologies. In this chapter we shall consider possible interaction between these topics, assessing the implications for the output growth rate and output fluctuations. We shall discuss three different approaches to this issue, giving different results which will be separately analysed.

We first consider a simplified model in which the diffusion of new technologies is taken as exogenous. In this case we use a modified version of the model presented in Romer (1987) and discussed in Jovanovic and Lach (1993). We then consider an extension of the Grossman and Helpman model (1991) which takes the effects of knowledge diffusion into consideration (Shulstad 1993). Finally, we analyse a model where the diffusion process is endogenised, partly by using the integrated model analysed in the previous chapter, and incorporated in the model by Romer (1990a, 1990b).

4.2 Exogenous Diffusion of New Technologies and Output Fluctuations

The first approach considers a model in which the number and also the use of goods varies over time. Technological shocks arise from the invention of new goods, which, through their progressive use, cause output fluctuations. This approach allows one to estimate the effects of technological shocks on output and, thus, contrasts with the hypothesis of Real Business Cycle models which consider technology as a residual variable with special stochastic characteristics.

The aggregate production function is given by

$$(4.1)\quad Y_t = L_t^{1-\alpha} \int_0^{A(t)} x^{\alpha}(i,t)\,di$$

where L_t represents labour input, $x(i,t)$ is the quantity of capital goods (i) used in production at time t and $A(t)$ the number of capital goods available at time t. If the size of the market does not affect the rate of adoption of each capital good, $x(i,t)$ may be defined as proportional to the stock of the labour force. Product (i) is introduced at time $v(i)$, and the corresponding output at time t depends on the age of the product $(t - v(i))$. Using these hypotheses it is possible to define $x(i, t)$ as

$$(4.2)\quad x(i,t) = L_t h(t - v(i))$$

New products are differentiated and characterised by different relative weights in the production process. To capture these differences it is assumed that

$$(4.3)\quad h(i)(t-v(i))^{\alpha} = \varphi(t-v(i);\theta(v(i)),\varepsilon(i,t))$$

where θ and ε are casual shocks affecting respectively all products of vintage v and the single product *(i)*. $\varepsilon(t,i)$ is the specific shock attached to good *(i)* with cumulative distribution $G(\varepsilon)$. Now define $f(t\text{-}v,\theta)$ as the average output at time t of products of vintage v:

$$(4.4)\quad \int \varphi(t-v,\theta,\varepsilon)dG = f(t-v,\theta)$$

and per capita income may then be defined as

$$(4.5)\quad \frac{Y_t}{L_t} = y_t = \int_0^A f\left[t-v(i),\theta(v(i))\right]di$$

We assume that $A(t)$ grows at a constant exponential rate g_a, and thus $A(t)=e^{gat}$

Equation [4.5] may be modified by changing the integration variable from the product name *(i)* to its vintage *(v)* thus yielding:

$$(4.6) \quad y_t = g_a \int_{-\infty}^{t} e^{g_a v} f(t - v(i), \theta(v)) dv$$

This transformation depends on the relationship between the variables i and v, where $i = e^{gav}$.

Taking the age of the intermediate goods $((\tau = t-v))$, allow us to modify equation [4.6] into

$$(4.7) \quad y_t = g_a e^{g_a t} \int_{0}^{\infty} e^{-g_a \tau} f(\tau, \theta(t - \tau)) d\tau$$

The integral in equation [4.7] is the moving average of past values of θ. This equation suggests that there are $g_a e^{g_a(t-\tau)}$ products of age τ and each product contributes to output for an amount $f(\tau, \theta(t-\tau))$, and the integral then represents the sum of all ages of intermediate goods. For the sake of simplicity [4.7] may be written in a more compact form:

$$(4.8) \quad y_t = e^{g_a t} Z_t$$

where

$$Z_t = g_a \int_{0}^{\infty} e^{-g_a t} f(\tau, \theta(t - \tau)) dt$$

Jovanovich and Lach show that if the stochastic process $\{\theta_t\}$ is stationary, $log y_t$ is stationary around the trend g_a, which is therefore the long-run growth rate.

Under these circumstances g_a does not depend on the function f, (which contains the time lags of the diffusion process of intermediate goods). In other words, the diffusion process does not have long-run effects on the growth rate although it may, affect long-run output levels.

To test how the diffusion process affects the cyclical component of output, one must assume a particular parametrization of the components of Z_t. In particular, it is assumed that in accordance with the theoretical and empirical literature of the third chapter, diffusion follows a logistic path. In other words, the components of Z_t are described by:

$$(4.9) \quad \varphi = (1 - e^{-\beta\tau})\theta \qquad \tau > 0$$

The parameter θ represents the market share of each product for $\tau \rightarrow \infty$. A high value of θ denotes the relative importance of products of vintage v in the production process. The parameter β shows the diffusion speed, which is assumed identical for each product. Substituting this parametrization in [4.4] we get

$$(4.10) \quad f(\tau,\theta) = (1 - e^{\beta\tau})\theta$$

From [4.8] we then have

$$(4.11)\quad Z_t = \quad g_a \int_0^{\infty} e^{-g_a \tau}(1 - e^{-\beta\tau})\theta(t-\tau)d\tau$$

Assuming that the stochastic process θ is stationary yields:

$$(4.12')\quad E(\theta) = \mu$$
$$(4.12'')\quad Var(\theta) = \sigma^2$$
$$(4.12''')\quad Cov(\theta_t, \theta_s) = 0 \qquad \text{se} \quad t \neq s$$

The effect of the diffusion process on output levels can be defined through the mean of Z_t:

$$(4.13)\quad E(Z_t) = \frac{\beta\mu}{\beta + g_a}$$

Equation [4.13] shows how the mean of Z_t is a growing function of the diffusion speed β. Jovanovich and Lach also show that the autocorrelation coefficient (r_k) of the logarithm of Z_t is negatively affected by diffusion speed and positively affected by the long-run growth rate of output (g_a) for low values of the lags of the autocorrelation coefficient (k). On the other hand, the value of r_k decreases with g_a. for high values of k. Thus we have

$$(4.14)\quad r_k = e^{-g_a k}\left[1+\frac{g_a}{\beta}(1-e^{\beta k})\right]$$

This model allows to assess and compare the autocovariances implied by [4.14] with those derived from aggregate series on output. For this purpose, however, one needs to define the parameters β, σ, μ and g_a. Jovanovich and Lach use the data described in Gort and Klepper (1982), where a historical analysis is presented of the diffusion of the main innovations which have characterised the twentieth century, giving information on prices, sales, production and the life cycle of products. Using this data Jovanovich and Lach estimate the parameters which affect the autocorrelation function (4.14). This procedure enables one to analyse technological shocks by direct estimate and not as a pure residuals as in the Real Business Cycle models (in which the state of technology is a non-observable variable and is thus modelled as an autoregressive process). Instead in the approach proposed by Jovanovich and Lach, the state of technology is no longer a residual, as the parameters which characterise the diffusion process are estimated and the cyclical effects are then derived. In this framework, diffusion has only level effects and does not affect the long-run growth rate of the economy.

However, the results of the empirical test proposed by Jovanovich and Lach are not robust, suggesting that the diffusion of new technologies explains short-run output fluctuations well, while at higher frequencies the model loses at least some of its explanatory power.

4.3 Knowledge Diffusion and Growth

One of the common results of the growth models analysed in the second chapter is that the growth rate depends on the scale of the economy. In other words, economies with a higher stock of human capital or labour force exhibit higher long-run growth rates. However, this theoretical conclusion does not find significant empirical support, as suggested in Jones (1995). If knowledge diffusion is introduced, this scale effect may be reduced or ruled out, thus generating a long-run growth rate which is independent of the size of the economy.

These arguments may be taken into account by using the specification adopted in the second chapter and dealing with the model proposed by Grossman and Helpman (1991) and later by Schulstad (1993). We first summarise the fundamental equations of the theoretical model, then consider the effect of knowledge diffusion.

The economy is composed of a fixed stock (*L*) of labour distributed between the research and manufacturing sectors. The unit wage at time t is equal to $w(t)$ and at any time there are $n(t)$ goods produced by monopolistic firms.

The demand side is defined by equation [2.72] described in the second chapter. The single producer possesses simple technology which needs one unit of labour per unit of output. The marginal cost for each producer is therefore equal to unit wage *w(t)* and in equilibrium the producer of good *i* will fix the price *p(t)* according to

$$(4.15)\quad p(t) = \frac{w(t)}{\alpha}$$

where α is the parameter which defines aggregate demand as in equation (2.72).

Profits of the single producer are $\pi = (1 - \alpha)/n(t)$ and the corresponding quantity produced is $[n(t)\ p(t)]^{1}$. Total labour demand in the manufacturing sector is therefore equal to $1/p(t)$. If we define ϑ (t) as the value of a firm, the no-arbitrage condition presented in the second chapter is

$$(4.16)\quad \frac{1-\alpha}{n(t)} + \frac{\dot{\vartheta}(t)}{\vartheta(t)} = r$$

where *r* is the equilibrium interest rate. The growth of the number of new products is derived from equation [4.17], which implies a constant exponential growth rate:

$$(4.17)\quad \dot{n} = \frac{L_R A_n}{b}$$

where L_R is the labour force employed in the research sector, A_n the aggregate stock of knowledge and b the productivity of the labour force. The equilibrium between demand and supply for labour implies

$$(4.18)\ \frac{1}{p(t)} + \frac{b\dot{n}}{A_n(t)} = L$$

The condition of free entry into the market implies equality between the development cost of a new product and the profits gained from its production. We therefore have

$$(4.19)\quad \frac{w(t)b}{A_n(t)} = \vartheta$$

It is now necessary to specify the role played by $A_n(t)$, the stock of knowledge, which is incorporated in the goods available at any time t.[1] Contrary to the hypothesis of the previous models it is assumed that past inventions give a greater contribution to the stock of knowledge than the more recent ones. In other words, it is assumed that

$$(4.20)\quad A_n(t) = \int_{-\infty}^{t} \dot{n}(s)(1-e^{-\beta(t-s)})ds$$

[1] It is assumed, as in the Romer model, that knowledge is a non-rival and non excludable good.

where β is a positive parameter which reflects the diffusion speed of knowledge. This specification is crucial as it can reduce or even eliminate the dependence of the growth rate on the size of the economy. One should note that as $\beta \to \infty$ the hypothesis of the Grossman and Helpman model holds as $A_n(t) \to n(t)$.

Denote V as the reciprocal of the aggregate value of a firm in the manufacturing sector ($V \equiv \frac{1}{n\vartheta}$) and γ_n as the growth rate of knowledge ($\gamma_n = \frac{\dot{n}}{n}$), which also determines the steady state growth rate of the economy. From [4.16] and the fact that $\frac{\dot{V}}{V} = -\frac{\dot{n}}{n} - \frac{\dot{\vartheta}}{\vartheta} = 0$ in the steady-state we get

$$(4.21)\quad (1-\alpha)V = \gamma_n + r$$

If we assume that the economy is in steady state from $s = -\infty$ equation [4.20] may be simplified as

$$(4.22)\quad A_n = \left(1 - \frac{\gamma_n}{\beta + \gamma_n}\right)n$$

Combining [4.22] with [4.15], [4.18] and [4.19] yields:

$$(4.23)\quad \alpha bV + b\gamma_n = L\left(1 - \frac{\gamma_n}{\beta + \gamma_n}\right)$$

From [4.22] and [4.23] the balanced growth rate of the economy (γ_n) may be derived and in this case depends on the rate of knowledge diffusion:

$$(4.24)\quad \gamma_n = -\frac{1}{2}(\beta + \alpha r) + \frac{1}{2}\left[(\beta - \alpha r)^2 + 4\beta\frac{L}{b}(1-\alpha)\right]^{\frac{1}{2}}$$

Indeed, the parameter which defines diffusion speed (β) affects the long-run growth rate. However it may also be endogenised to offset the typical scale effect of endogenous growth models. In particular, Schulstad (1993) shows that, if β is a decreasing function of the stock of the labour force, a country with a greater endowment of labour force does not necessarily grow faster than other less endowed countries.

4.4 Endogenous Diffusion of New Technologies and Growth

In this section we propose a growth model which endogenises the diffusion path using the approach described in integrated models of technological diffusion. Diffusion is generated by the interaction of the demand and supply sectors of new technologies, which are now included in an aggregate growth model based on the Romer specification (Romer 1990a, 1990b).

Consider a closed economy with three sectors :

a) a final good sector;

b) an intermediate (producer durables) goods sector;

c) a research sector.

In the final goods sector, output is produced by means of physical labour L (unskilled workers) and physical capital *(x)*. The latter is assumed to be the sum of an infinite number of distinct types of producer durables (x_i). The production function is given by

$$(4.25) \qquad Y_f = g(L) \sum_{i=1}^{\infty} x_i^{\phi}$$

and is assumed to be homogeneous of degree one; *g(L)* is homogeneous of degree $1-\phi$ and x of degree ϕ.

The research sector produces knowledge, which is incorporated into designs. Each design is then sold to a single firm in the producer durables sector which acts as a monopolist. Each firm in this sector then produces a single capital good which is acquired by the final goods sector.

Output in the intermediate and research sectors is described by simple technologies being produced by means of labour and the available stock of knowledge[2]. However, the intermediate sector uses specialised workers *(T)*, whereas the research

[2] It is assumed, as in Romer (1990), that the stock of knowledge (A) is a non rival and non excludable good.

sector uses researchers *(R)*. The intermediate sector is described by monopolistic suppliers. The technology for the production of each capital good is given by

$$(4.26) \quad z(i) = T(i)A$$

where $z(i)$ is the output of capital good (i) at time t, $T(i)$ is the constant flow of labour input (specialised workers) used in the production of capital good i and $A(t)$ is the available stock of knowledge.

The production function in the Research sector is given, as in Romer, by

$$(4.27) \quad \dot{A} = \delta RA$$

where $\dot{A}$ is the number of designs produced at time t, being proportional to the existing stock of knowledge $A(t)$. R is the amount of human capital employed in the research sector (researchers) and δ is a positive productivity parameter.

Treating i as a continuous variable the sum on the *RHS* of equation (4.25) can be substituted by an integral. At any time (t) a firm will use only the durables that have already been invented. The range of integration varies between 0 and $A(t)$, where $A(t)$ is the number of capital goods invented and produced by time t. Equation (4.25), therefore, becomes

$$(4.28) \quad Y_f = g(L)\int_0^{A(t)} x(i)^{\phi}\,di$$

A single aggregate representative firm is used to describe the final output sector. The production function of the representative firm determines the demand for new technology, i.e., the demand for capital goods. Hence, technological diffusion has to be analysed as intra-firm diffusion, with the representative firm acting as a repeating buyer of capital goods produced by the supplying sector. In this sector each capital good is produced by a single monopolist and diffusion results from supply/demand interaction. This type of approach develops the models presented by Stockey (1979) and by Ireland and Stoneman (1986).

Define $f(x(i))$ as the increase in revenues of the representative firm in the final output sector generated by the additional purchase of an extra unit of capital goods (i) in time t. Moreover, assume that the increase in revenue is perpetual; this implies a present value gain from acquisition of $f(x(i))/r$, where r is the interest rate. The cost of acquisition of capital goods (i) in time t is $p(i)$. We can now more formally show the problem facing the representative firm. Two conditions must be satisfied:

$$(4.29) \quad f(x(i)) \geq rp(i)$$

$$(4.30) \quad -\dot{\hat{p}}(i) + rp(i) - f(x(i)) \leq 0$$

where $\dot{\hat{p}}$ represents the buyer's expectation of the change in price, equivalent to the discrete time form : $p^{\bullet}_{t+1} - p_t$

Condition (4.29) is a simple profitability condition and (4.30) is the arbitrage condition (see Ireland and Stoneman (1986) and the discussion of section 3.3). We assume that the buyer has myopic expectations and in this case condition (4.30) collapses into (4.29).

Following Ireland-Stoneman (1986), we can then write a dynamic demand function of the type:

$$(4.31) \qquad -\dot{p}(i) + rp(i) = -\frac{1}{r} f_x z(i) + f(x(i))$$

where $z(i)$ is the actual purchase of capital good (i), i.e., it represents the difference in the cumulative production of the capital good (i) between time t and $t+dt$ (i.e., $z(i) = \dot{x}(i)$).

The representative firm in the final output sector is assumed to maximise (4.22) by the choice of $x(i)$

$$(4.32) \qquad \text{Max} \int_0^A \left[(g(L)x(i)^{\phi} - rp(i)x(i) - w_L L \right] di$$

where $rp(i)$ is the rental price of capital good *(i)*, w_L is the unit wage of unskilled workers and L is the fixed number of unskilled workers used in the production of consumer durables. Given that the wage for unskilled workers is determined by the usual marginal productivity rule, we have

$$(4.33)\quad w_L = g_L \int_0^A x(i)^{\phi}\, di$$

which after substitution in (4.32) yields:

$$(4.34)\quad Max \int_0^A \left[g(L)x(i)^{\phi} - rp(i)x(i) - g_L x(i)^{\phi} L \right] di$$

Differentiating under the integral sign, we get the inverse demand function for each capital good, that is

$$(4.35)\quad rp(i) = \phi x(i)^{\phi - 1}\Gamma$$
$$\text{where}\quad \Gamma = \left(g(L) - g_L L\right)$$

substituting in (4.30) yields (4.36) as the dynamic demand function for capital good *(i)*:

$$(4.36)\quad -\dot{p}(i)+rp(i)=-\frac{1}{r}\phi(\phi-1)\Gamma x(i)^{\phi-2}z(i)+\phi\Gamma x(i)^{\phi-1}$$

In the sector that produces capital goods the crucial assumption is that all capital goods are produced by identical monopolistic firms, which have bought the design of the capital good from the research sector[3]. The objective of each firm can be described by the usual inter-temporal maximisation problem. It is assumed that the production of each capital good starts as soon as the capital good is invented. The technology in this sector is given in equation (4.26). Operating profits for a monopolistic supplier who enters the market at time v are defined by

$$(4.37)\qquad \Pi=\int_{v}^{\infty}(p(i)-\mu(i))z(i)e^{-r(t-v)}dt$$

where $p(i)$ and $\mu(i)$ are the unit price and unit production costs of capital good i and $z(t)$ is the actual production level of capital good i in time t. Given the production function (4.26), total production costs are defined as follows:

$$(4.38)\qquad C=w_T\,T$$

[3] The price of a patent corresponds to the profit stream that the owner can extract from it. Therefore, this implies an intertemporal zero profit constraint for the monopolistic supplier as in Romer (1990) and Grossman and Helpman (1991).

where w_T is the wage for specialised workers T. Average rental production costs $r\mu(i)$ are defined as

$$(4.39) \quad r\mu(i) = \phi x(i)^{\phi-1}\Gamma$$
$$\therefore (4.39') \; r\mu(i) = rp(i)$$

Hence, the rental price of capital good *(i)* will equal the unit production cost of good *(i)*[4]. Integrating (4.37) by parts yields:

$$(4.40) \quad \Pi = \int_v^{\infty} (-\dot{p}(i) + rp(i) - \dot{\mu}(i) - r\mu(i))x(i)e^{-r(t-v)}dt$$

Substituting (4.36) into (4.40) yields:

$$(4.41) \; \Pi = \int_v^{\infty}\left[\left(-\frac{1}{r}\phi(\phi-1)g(L)x(i)^{\phi-2}z(i) + \phi g(L)x(i)^{\phi-1}\right) + \dot{\mu}(i) - r\mu(i)\right]x(i)e^{-r(t-v)}dt$$

[4] Recall that : $w_T = MP*MR = A*MR$. Hence $C = A*MR(z(i)/A) = MRz(i)$. From 4.35 we have:

$$MR = \frac{1}{r}\phi x(i)^{\phi-1}\Gamma \quad \therefore C = \frac{1}{r}\phi x(i)^{\phi-1}\Gamma z(i) = p(i)z(i)$$

Average rental costs are defined as : $r\mu(i) = \dfrac{rC}{z(i)} = \dfrac{rp(i)z(i)}{z(i)} = rp(i)$

The supplier's problem is to maximise (4.41) under the following two constraints:

$$(4.41') \quad \dot{x}(i) = z(i)$$
$$(4.41'') \quad z(i) \geq 0$$

The Hamiltonian conditions of the problem are derived in the Appendix. The optimal trajectory for capital good *(i)* is

$$(4.42) \quad \phi\Gamma x(i)^{\phi-1} = r\mu(i) - \dot{\mu}$$

and given the characterisation of the cost function $\mu(i)$, this yields:

$$(4.43) \quad \phi\Gamma x(i)^{\phi-1} = r\phi\Gamma x(i)^{\phi-1} - \phi(\phi-1)\Gamma x(i)^{\phi-2} z(i)$$
$$(4.43') \quad \therefore z(i) = \frac{r-1}{\phi-1} x(i)$$

Given that $z(i) = \dot{x}(i)$, and normalising so that $x_0(i) = 1$, the supply trajectory may be expressed as

$$(4.44) \quad x(i) = e^{\frac{r-1}{\phi-1}(t-v)}$$

From the production function of the intermediate sector it follows that $\frac{\dot{A}}{A} = \frac{\dot{z}}{z}$.

This implies:

$$(4.45) \quad \delta R = \frac{r-1}{\phi - 1}$$

Equation (4.45) implicitly defines the value of R that ensures a balanced growth path[5]:

$$(4.46) \quad R = \frac{r-1}{\phi - 1}\frac{1}{\delta}$$

From the production function (4.26) and from (4.46) the value of T is defined in (4.47)[6]:

$$(4.47) \quad T = \frac{r-1}{\phi - 1}$$

[5] As r, ϕ and δ are parameters, one can think of R as the ratio of researchers to the sum of unskilled workers , the constant flow of technicians and researchers.

[6] As in the case of equation (4.41) T can be thought of as the ratio of the constant flow of technicians to the sum of unskilled workers, researchers and the constant flow of technicians .

Using the transformation adopted in Jovanovic and Lach (1993) we can express equation (4.28) in terms of capital vintage *(v)* instead of capital name *(i)*. Given that: $i=e^{\delta Rv}$ we get:

$$(4.48)\quad Y_f = g(L)\int_{-\infty}^{t} \delta\, Re^{\delta Rv}\, x(t,v)^{\phi}\, dv$$

Substituting the supply trajectory (4.44) into (4.48) yields:

$$(4.49)\quad Y_f = g(L)\int_{-\infty}^{t} \delta\, Re^{\delta Rv}\left(e^{\frac{r-1}{\phi-1}(t-v)}\right)^{\phi} dv$$

If we consider the age of capital goods, instead of their vintage, we get

$$(4.50)\quad Y_f = g(L)\int_{0}^{t} \delta\, Re^{\delta R(t-\tau)} e^{\frac{r-1}{\phi-1}\phi\tau}\, d\tau$$

where τ is a new variable that defines the age *(t-v)* of capital goods. Given that $\delta R = \dfrac{r-1}{\phi-1}$, we then have

$$(4.51)\quad Y_f = g(L)\delta Re^{\delta Rt}\int_0^t e^{(\phi-1)\delta R\tau}d\tau$$

$$\therefore (4.51')\quad Y_f = g(L)\left[\frac{e^{\phi\delta Rt}}{\phi-1}-\frac{e^{\delta Rt}}{\phi-1}\right]$$

which implies that

$$(4.52)\quad \frac{\dot{Y}_f}{Y_f} = \frac{\delta R\left[e^{\delta Rt}-\phi e^{\phi\delta Rt}\right]}{\left[e^{\delta Rt}-e^{\phi\delta Rt}\right]}$$

where (4.52) gives the rate of growth of final output on the steady state growth path. On this path (4.50) suggests that there are ($\delta\,\mathrm{Re}^{\delta R(t-\tau)}$) capital goods of age τ, each used according to the supply trajectory given in equation (4.44). From (4.52) the final output growth rate converges to δR as $t \to \infty$. Asymptotically the economy converges to a steady state where all the variables increase at the common growth rate , $\delta R = \dfrac{r-1}{\phi-1}$.

To generate a balanced growth path, the value of R is determined by parameters r, ϕ and δ in equation (4.46). In the Romer specification, the growth rate of the economy is determined either by the allocation of human capital to the research sector (Romer 1990a, 1990b) or by the parameters that define the production function (Rivera Batiz-Romer 1991). In particular, in Romer (1990a) the balanced growth rate is equal to

δH_a, where H_a is the allocation of human capital to the research sector.[7] However, H_a is determined by the following equation:

$$(4.53) \qquad H_a = H - \frac{r\alpha}{\delta\phi}$$

where H is the fixed total amount of human capital, which is the sum of the human capital employed in manufacturing (H_y) and the human capital in the research sector (H_a); r is the interest rate, δ is a positive parameter reflecting the productivity of human capital in research and α is a parameter of the production function of the representative firm in the final output sector.[8] This expression for human capital in research takes the interest rate as a parameter as in the specification we have adopted. The main features of equation (4.53) are:

a) there is a scale effect on the growth rate, i.e., the growth rate is positively related to the initial endowment of human capital;

b) a decrease in the interest rate positively affects human capital in research and, therefore, the growth rate.

In the specification adopted in this section the growth rate is determined by the parameters which define the diffusion of new capital goods, i.e., the interest rate r and the coefficient ϕ of the aggregate production function in the final output sector.

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[7] The variable R is equivalent in our specification to the variable H_a used in the Romer model.

[8] In the Romer specification it is assumed that the production function in the final output sector takes the form: $g(H_y,L)=H_y^{\alpha(1-\alpha)}L^{(1-\alpha)(1-\phi)}$ where Hy is human capital in manufacturing and L physical unskilled labour.

Thus in this new model there is still the positive effect of a decrease in the interest rate on the growth rate of the economy, as in the Romer model. However, in addition, an increase in ϕ has a positive effect on the growth rate, as it involves a higher diffusion path derived from the shift of the demand function of capital good *(i)*. The opposite effect is obtained if ϕ is reduced. In addition, this model contrasts with Jovanovich and Lach's conclusion that diffusion has only level rather than growth effects in the long-run.

4.5 Model implications

One important implication of the model we presented in the previous section is that the growth rate of the economy is now affected by parameters which are influenced by policy, namely the interest rate r and the parameter ϕ that define the production function in the sector producing final goods. In turn, both r and ϕ determine the diffusion path of new capital goods, suggesting that diffusion may have a long-run effect on growth.

This is a distinctive feature of our model compared both with the Romer model and with more recent R&D endogenous growth models (Jones 1995b).

In Romer, we have a positive growth effect, eventually stimulated by policy action, generated by the decrease in the interest rate, which is associated with an increase in human capital devoted to research and through this route to an increase in the output growth rate.

No other policy intervention can stimulate growth, because neither the total labour force, nor the magnitude of the parameter which defines the unit cost of producing new producer durables, affect the growth rate of the economy.

In Jones (1995b) growth is independent of policy, as the model predicts that long-run growth is just proportional to the rate of population growth. As we mentioned before, this conclusion is derived by assuming decreasing returns in the production of new innovations, thus bringing us back to the conclusion of the standard neo-classical model, in which long-run growth is independent of the structural characteristics of the economy.

The new theoretical model we proposed in the previous sections maintains the Romer specification for the research sector, while modifying the representation of the final output and producer durables sectors as they have different production functions. This is a new specification, because in the Romer model the sectors producing final output and capital goods share the same production function, and thus they can be aggregated into one single manufacturing sector.

In our specification the interaction between these two sectors is driven by the demand and supply of new capital goods, which are used by the final goods sector to produce final output.

In addition, we endogenise the supply trajectory of new capital goods by solving the problem of the monopolistic supplier (entering the market at a certain point in time say, v), for a given demand function which in turn is derived from the profit maximisation problem of the representative firm in the final good sector. The supply trajectory therefore defines the diffusion path of the new technology, i.e., the diffusion path of the new capital good.

This diffusion path is determined by equation (4.44) and it depends on two parameters, namely the interest rate, r, and the parameter which characterises the production function of the final good sector, ϕ. Both parameters are < 1 and hence an increase in the interest rate shifts the diffusion path downward, while a decrease in the interest rate has the opposite effect. In addition, an increase in ϕ shifts the diffusion path upward, which is however shifted downward by a decrease in ϕ.

Thus there is a clear growth effect of the parameters which define the diffusion path, suggesting that a higher diffusion path involves a higher long-run growth rate for the economy, brought about by the increase in demand for new capital goods. Indeed, the parameter ϕ determines the marginal productivity of each capital good in the final good sector and consequently their demand function, as is specified in equation (4.35). An increase in ϕ shifts the demand curve of capital good i outward, and through its interaction with the supply sector increases the supply too, thus generating a higher diffusion path..

In this framework, stimulating (e.g. subsidising) the demand for producer durables goods in the final good sector, shifts the demand function upward, and, through interaction with the supply sector and the resulting diffusion path, stimulates the output growth rate. It is worthwhile to recall that in our specification the interaction between the demand and supply sectors of new producer durables goods is simultaneous, implying that shifts in the demand curve are instantaneously reflected in the supply trajectory. This is the mechanism through which the parameter ϕ affects both the demand and supply sectors, which in turn determine the diffusion path.

Table 4.1

Theoretical models	*Determinants of output growth (g)*	*Implications*
Romer (1990a, 1990b)	$g=\delta H_a$, where; $H_a = H - \frac{r\alpha}{\delta\phi}$	**growth effect of changes in interest rates; Total labour force and the cost of the units of producer durables that are produced have no effect on the growth rate.**
Jones (1995b)	$g = \frac{\lambda n}{1-\gamma}$	**long-run growth is proportional to population growth**
Our model with endogenous diffusion	$g=\delta R$, where; $\delta R = \frac{r-1}{\phi - 1}$	**growth effect of interest rate; growth effect of the diffusion path of new technologies, i.e., new producer durables goods.**

Table (4.1) summarises the main implications of the theoretical models which are more closely related to the model we presented in section (4.4). In the Romer model the only clear growth effect is attributable to a change in the interest rate, whereas neither changes in the total labour force nor changes in the cost of producing producer durables affect the long-run growth rate of the economy.

This result depends on the structure of the model, which requires an equilibrium between returns to human capital in manufacturing and research and hence the positive effect of a decrease in capital production costs is exactly offset by the increase in the remuneration of human capital in research. An increase in the total labour force has similar effects, in that there is first an increase in the marginal product of human capital in manufacturing and, at the same time, there is an increase in the marginal product of each of the producer durables, causing, therefore, an increase in the monopoly rent of researchers. These are two offsetting effects, which leave the allocation of human capital between manufacturing and research unchanged.

Jones' work (1995b) has strong implications, as the growth rate is just proportional to the population growth rate and therefore is invariant to policy manipulation. This model is specified like the Romer model but assumes that there are decreasing returns to R&D, as we discuss in section (2.6).

In our model, the growth effect of a change in the interest rate is reinforced, as it contributes, on the one hand, to the determination of the value of human capital in research, and, on the other hand, to the determination of the diffusion path of new producer durables. This is important for policy because policy aimed at stimulating growth may be mainly concerned with the reduction of the interest rate, which causes a higher allocation to human capital in research and a larger supply (and use) of new intermediate goods.

In addition, there is another clear growth effect which derives from changes in the parameter ϕ, which defines the diffusion path of new capital goods. An increase in ϕ again causes an increase in human capital devoted to research and an upward shift of the diffusion path, thus increasing the long-run growth rate. This result underlines the difference with the Romer model and also with the specification adopted in Jones, in that we now have a clear distinction between the sectors producing and using new capital goods. The interaction between the supply and the demand sectors determines the diffusion path, which in turn affects the long-run growth rate of the economy.

4. 6 Conclusions

We have first analysed a methodology to assess the effects of an exogenous diffusion of innovations on output fluctuations. This approach allows in principle for an estimate to be made of the impact of technological shocks on output growth.

We have underlined some drawbacks of endogenous growth models which rely upon the hypothesis of instantaneous diffusion of innovation and knowledge, and we have then considered the effect of knowledge diffusion in a modified version of the model described in section 2.3. In addition we have proposed a different version of the Romer model which includes the diffusion path of new capital goods.

In the former case, i.e., introducing lags into the acquisition of knowledge, the scale effect no longer holds since a higher diffusion speed can offset the effect generated by the size of the economy. In the latter case, introducing a diffusion path for new capital goods generates a growth rate which depends on the parameters defining this diffusion process. Thus diffusion does affect the long-run growth rate of the economy. This finding is a new refinement of R&D endogenous growth models and it also contrasts with previous models suggesting that diffusion may have only long-run level effects rather than growth effects.

Appendix

A1. Integration by parts. Recall that

$$\int_0^{\infty} f'(t)g(t)dt = f(t)g(t)\Big|_0^{\infty} - \int_0^{\infty} f(t)g'(t)dt$$

and $\dot{x} = z$

A2. Hamiltonian conditions. From the maximisation of equation (4.41) under conditions (4.41') and (4.41'') we get the following Hamiltonian conditions:

A.2.1. $H = \left[-\frac{1}{r}\phi(\phi-1)g(L)x^{\phi-2}z + \phi g(L)x^{\phi-1} + \dot{\mu} - r\mu \right] xe^{-r(t-v)} + \lambda z$

A2.2. $H_x = -\dot{\lambda}$

A2.3. $H_z = 0$

A2.4 $H_\lambda = z$

Differentiating with respect to time A2.3. and substituting into A2.2. yields equation (4.42).

CHAPTER V

5. Empirical Investigation: An Introduction

A distinctive feature of the previously analysed endogenous growth models is that permanent changes in variables that are potentially affected by policy affect the long-run growth rate of the economy. On the one hand, the so called AK models (Romer (1986), Rebelo (1991)) emphasise the role of physical capital in the determination of the long-run growth rate. On the other hand, the R&D-based growth models (Romer (1990a,1990b), Grossman and Helpman (1991), Aghion and Howitt (1992)) stress the role of resources devoted to technological innovation. The theoretical model we propose in Chapter 4 falls within the context of the R&D-based models, underlining, in addition, the role of technological diffusion in the growth process and suggesting that policy aimed at increasing diffusion may affect long-run growth.

In all cases, the implied results contrast with the conclusion of the traditional neo-classical model, in which long-run growth depends only on exogenous technological progress, thus ruling out any long-run effect of variables affected by policy intervention. This conclusion is also shared by endogenous growth models which assume decreasing returns in the research sector (Jones 1995a).

Thus one primary task of any empirical analysis is to establish the role and the kind of relationship between these different aspects of economic growth theory, namely research activity, investment and output growth.

This kind of investigation may help in understanding the underlying sources which lead to economic growth and may contribute to the testing of whether endogenous growth model predictions are correct and robust.

Empirical investigations which originate from theoretical analysis mainly emphasise how physical capital accumulation is a strong concomitant to output growth in the growth experience of many different countries. This is the typical result of many cross-country analyses, which find a significant correlation between the share of investment in GDP (or the rate of growth in the capital stock) and the rate of growth in per capita-income. This regular result in such empirical studies (Romer 1987, Barro (1991), Summer Heston (1991)) led to the study of capital accumulation as the driving force behind the growth process.

Moreover, the analysis by De Long and Summers (1992a) emphasises, within this framework, the role of machinery and equipment investment in explaining the growth rate of a large set of economies, thus concluding that this kind of investment may be seen as the key to economic growth. However, correlation does not mean causation. Capital accumulation might also occur in response to knowledge accumulation, as technological innovations raise the marginal productivity of capital and thus make machinery and equipment investment more profitable. This consideration is consistent with other cross-country evidence, which underlines the high and positive correlation between the growth rate of capital stock and the estimated gain in total factor productivity (Baumol, Blackman and Wolff 1989).

Another important consideration which justifies the empirical analysis of the following chapters deals with the problems that arise in interpreting results from growth-accounting studies, which makes them inappropriate for drawing inferences about the underlying causes of economic growth.

The first problem reflects the fact that the impact of technological change on output growth is understated because changes in the quality and variety of goods and services change over time and these are not adequately considered in the national income accounts.

The second problem is associated with the presence of externalities or increasing returns in the production process, which generate a bias in the usual estimate of Total Factor Productivity (TFP).

The third and most relevant problem of growth accounting derives from the impossibility of drawing inferences about the underlying causes of economic growth. Capital accumulation may, for example, account for a certain proportion of output growth. However, this decomposition does not allow us to infer the causality linkages behind these facts. It could be possible that firms attempts to further mechanise the production process bring about new capital accumulation. However, it could be also possible that new investment in machinery and equipment are made in response to new technological conditions, which may imply that new extra equipment is required to produce new invented goods or because innovative manufacturing techniques make it profitable to install more (and different) machines. This latter case is the typical representation suggested by R&D endogenous growth models.

In these cases capital accumulation cannot be taken as the underlying source of output growth, rather, following the R&D growth models, industrial research may be thought of as the primitive force behind output growth.

Thus a crucial task of any empirical investigation dealing with endogenous growth theories is to explain the nature of the links between industrial research and economic growth. There is much room for study in this framework, as there are still few studies analysing this relationship.

Using a panel data set drawn from 191 firms in the US manufacturing sector, Lach and Schankerman (1989) find that industrial R&D "Granger causes" capital investment, without any feedback, i.e., capital investment does not "Granger cause" R&D.

This approach, however, received few further improvements from empirical investigations, and in addition results are controversial, as we shall point out in Chapter 6. Thus there is the need to further test the characteristics of the link between R&D activity and investment, to provide a more detailed and precise picture of the forces underlying the growth process.

In Chapter 6 we shall analyse this issue in more detail, explicitly testing the relationship between R&D and investment for causality both in a time series and panel framework.

As we have previously underlined, capital investment is considered as one of the key factors in the growth process, in both the theoretical and empirical literatures. The R&D growth models emphasise more the role of technological innovation, as proxied by the resources devoted to R&D, while the AK models and the underlying empirical literature highlight the role of physical capital. In addition, De Long and Summer's investigation underlines how the machinery and equipment component of investment may be regarded as the crucial factor affecting growth.

This issue is, however, controversial, as the high correlation between investment and growth does not tell us anything about causation. Moreover, a two-way relationship may also be involved. An economy with an abundant supply of plant and equipment may, on the one hand, be expected to produce a relatively large output but, on the other hand, it may also be true that an economy with a larger output has more opportunities to build new plant and equipment.

This issue is crucial for policy because if capital accumulation were not significant in the determination of output growth, stimulating saving and investment would not be an efficient instrument for stimulating national growth. This is even more important in an international framework, in that the large capital stock of the industrialised countries would be the consequence rather than the cause of their wealth and thus not a good policy instrument for less developed countries.

The empirical evidence on this issue is not robust and, in addition, is controversial. In a recent study, Blomstrom, Lipsey and Zejan (1995) contrast De Long and Summers' conclusion, suggesting that growth induces subsequent investment, thus finding no evidence that fixed or equipment investment is the key to economic growth.

This analysis is, however, based on a large panel of countries which does not allow sufficient consideration of fixed effects determined by country-specific initial conditions.

Baumol, Blackmann and Wolff (1989) suggest that a two-way relationship may be more appropriate to explain the nature of the relationship between capital accumulation and growth, thus supporting Kuznets's (1973) view that there are times when physical capital accumulation strongly stimulated economic growth, but also times when the acceleration of growth precedes the growth of capital.

It is therefore crucial to analyse the characteristics of the relationship between growth and investment (particularly machinery and equipment investment), in order to determine the direction of the causation between these variables and therefore to test endogenous growth models empirically.

We test this relationship within a pure time series framework, which enables us to apply the concepts of short-run and long-run causality derived from the recent empirical literature on cointegration and error correction representation of dynamic econometric models. This distinction is crucial as it allows us to separate short-run and long-run influences which are not explicitly considered in the empirical literature. In addition, we analyse the effect of a permanent increase in the investment rate on the growth rate, to further test whether the theoretical predictions of endogenous growth models are consistent with the data.

In Chapter 7 we therefore analyse the causal relationship between investment in machinery and equipment and output growth, using time series data for the US economy over the post World War II period. Furthermore, we analyse the dynamic response of the output growth rate to a shock in the investment rate, to verify its impact in both the short and the long-run.

In Chapter 8 we apply these empirical tests to the UK economy to verify if they are typical of and thus specific to the US economy or, instead, they are stylised facts within many of the main industrialised countries.

CHAPTER VI

6. The Dynamics of R&D and Investment

6.1 Introduction

In the previous chapters we have analysed theoretically the impact of innovative activity on investment and output growth. In this chapter we analyse this relationship on empirical grounds, focusing on both time series and intersectoral data. One of the main predictions of the endogenous growth models we have analysed is the crucial role played by R&D and investment in the growth process. These models emphasise how knowledge generated in the R&D sector by the action of profit maximising firms is incorporated into blueprints used by firms in the manufacturing sector to produce final output. A strong link is thus implicitly assumed between R&D activity and investment in new machinery by firms in the manufacturing sector.

The causal link between R&D and investment has not however received the attention that it merits in the empirical literature on endogenous growth. Some, recent studies have tried to fill this gap by investigating the interaction between innovative activity and investment, following the seminal work by Schmookler (1966). He argued that investment in new capital goods is the driving force behind technological change (as proxied by a head count of patents) . In a more recent study, Lach and Schankerman (1989) investigate the dynamic interaction between R&D and investment for a panel of US firms and find that reverse causality holds, in that R&D Granger causes investment without any significant feedback. Using a panel of British industrial firms, Nickell and Nicolitsas (1996) show that R&D expenditure positively affects investment in most UK industrial sectors and that the reverse relationship does not hold. However, this result for the UK economy seems time-and-firm specific. Using a different panel of UK firms to replicate the Lach and Schankerman dynamic analysis, Toivanen and Stoneman (1997) find that investment Granger causes R&D and not the reverse.

In this chapter we set up an empirical framework to further test the possible causal linkages between investment and R&D, using aggregate data for the US economy on industrial R&D expenditure and investment in machinery and equipment over the period 1953-1993. This aggregate level approach is consistent with the modelling structure of new growth theory. Both the traditional Granger causality approach and the methodology implied by the theory of cointegration are employed. This analysis will be extended to a panel of 18 manufacturing sectors of the US economy for the period 1973-1993. In chapter eight we shall extend this analysis to the UK economy, comparing the results.

6.2 Innovative Activity and Investment

Before analysing our empirical findings, it is worth recalling the main findings reported in the empirical literature on this issue. In his seminal work Schmookler (1966) uses a head count of patents as a proxy for technological opportunities, noting that this indicator was associated with the distribution of investment among industries. The rationale behind Schmookler's argument lies in the effect of expected profitability on the investment decisions of firms. If we define Π_j as the expected profitability from a capital goods invention, j, we can derive a formal expression for profitability:

$$(6.1)\quad \Pi_j = p_j x_j - c_j x_j - E_j$$

where x_j is the output of capital good embodying the invention, p_j is the price of capital good j, c_j is the cost of manufacturing one machine and E_j is the expected cost of inventing.

It is also assumed that the share of the market captured by the new machine is a constant defined by

$$(6.2)\quad s_j = \frac{p_j xj}{S}$$

where S is the size of the market. Thus x_j may be expressed as

$$(6.3)\quad x_j = \frac{s_j S}{p_j}$$

Equation (6.1) now takes the form:

$$(6.4)\quad \Pi_j = s_j S - \frac{c_j s_j S}{p_j} - E_j$$

or

$$(6.5)\quad \Pi_j = s_j S\left(1 - \frac{c_j}{p_j}\right) - E_j$$

c_j/p_j is the cost-price ratio and it is assumed to be a constant, k, arguing that it reflects pricing practices based on fixed markup. Equation (6.1) then becomes

$$(6.6)\quad \Pi_j = s_j S(1-k) - E_j$$

Using equation (6.6), new machines will be invented if $s_j S(1\text{-}k) > E_j$. Given S and E_j new machines will be invented the larger the market share , s_j . Also, given S and s_j, invention will be negatively affected by E_j, the expected cost of invention. Schmookler underlines that the most important relation that emerges is, however, the positive effect of the size of the market, S, on the number of invented machines, given s_j and E_j.

The size of the market is proxied in Schmookler's investigation by the level of investment activity and looking at patenting activity in US railroads he finds support for the hypothesis implied by equation (6.6).

It is worth underlining, as suggested in Rosenberg (1974), that Schmookler's analysis ignores interindustry differences in the cost of invention and that patenting activity is just one of the possible proxies for technological opportunities.

In a more recent study, Lach and Shankerman (1989) empirically explore the dynamic interactions between innovative activity as proxied by R&D expenditure and investment for a panel of US firms in the scientific sectors during the period 1973-1981.

Their empirical model may be described by a simple vector autoregression model using its moving average representation :

$$(6.7)\quad rd_t = A_1 (L)\varepsilon_t + A_{12}(L)\eta_t$$

$$(6.8)\quad maceq_t = A_{21}(L)\varepsilon_t + A_{22}(L)\eta_t$$

where *rd* is the log value of R&D expenditure and *maceq* is the log value of machinery and equipment investment. A_{11}, A_{12}, A_{21} and A_{22} are polynomial in the lag operator L, and ε_t and η_t are white noise disturbances which summarise the impact of different random variables on *rd* and *maceq*.

In standard neo-classical models, equations (6.7) and (6.8) are implicitly assumed to be such that there is a contemporaneous interaction between R&D and investment.

Such models treat R&D and investment as increments in the existing stock of knowledge and physical capital respectively, under the assumption of profit maximisation subject to the cost of adjustment in both stocks of knowledge and physical capital. This justifies the inclusion of both ε_t and η_t in the R&D and investment equations. In other words, this hypothesis implies that the coefficients A_{ij} must be non zero in both equations.

Lach and Schankerman consider, on the other hand, the asymmetric hypothesis in which one random factor is idiosyncratic to one of the endogenous variable, thus imposing a causal linkage between the two variables.

They consider two different kinds of restriction on the parameters of equations (6.7) and (6.8). The first reflects what they define as the technological opportunities hypothesis, which implies that R&D activity reacts to factors such as advances in basic science, methods and techniques. These factors, therefore, do not affect investment, implying that either the coefficient on η_t or ε_t are zero in the investment equation.

If η_t represents the technological opportunities factor, one may impose the restrictions A_{22}=0 and $A_{12} \neq 0$.

On the other hand, one can think of a firm's investment as the reaction to an R&D success shock that represents an unpredictable output of R&D activity.

In this latter case, if η_t represents the R&D success shock the implied restrictions are: $A_{12}(L)=0$ and $A_{22}(L) \neq 0$.

In this second hypothesis, the autoregressive versions of equations (6.7) and (6.8) are:

$$(6.9)\quad rd_t = B_{11}(L)rd_{t-1} + \alpha\varepsilon_t$$

$$(6.10)\quad maceq_t = B_{21}(L)rd_{t-1} + B_{22}(L)maceq_{t-1} + \beta\varepsilon_t + \delta\eta_t$$

Parameters α, β and δ represent the instantaneous response to the shocks.

A standard Granger causality test allows Lach and Schankerman to conclude that R&D causes investment and not the reverse, thus imposing the above restrictions on equations (5.7) and (5.8).

In addition, the analysis of the response of each variable to a shock in ε_t and η_t, shows that the factors determining changes in long-term investment decisions are the same as the factors that determine R&D expenditure programs.

However, the factors that determine short-term investment fluctuations have little to do with R&D activity. This is what Lach and Schankerman define as the idiosyncratic factor. The impact of this shock declines sharply over time. These results seem, however, to be specific to the characteristics of the US economy. Using a different panel of UK firms to replicate the Lach and Schankerman dynamic analysis, Toivanen and Stoneman (1997) find that investment Granger causes R&D and not the reverse.

Jointly these findings underline that the relationship between innovative activity and investment is still a controversial issue, which needs to be analysed in more detail and with more appropriate empirical tests. This is the aim of the analysis we develop in this chapter using both time series and a panel data set. Aggregate data shows R&D expenditure in the industrial sector (with the exclusion of federal funds), while machinery and equipment investment derives from the OECD National Accounts estimates. The intersectoral data shows the OECD estimates of Business Enterprise Total Intramural Expenditure on R&D (BERD) and estimates of sectoral machinery and equipment investment for 18 manufacturing sectors over the period 1973-1993.

6.3 The Causality Between R&D and Investment: Traditional Granger Causality Tests

Traditional Granger causality tests are mainly concerned with the concept of precedence. *A* time series z_t is said to Granger cause x_t if the prediction of x_t can be improved upon by the inclusion of lagged values of z_t in the information set used for that prediction.

Formally the test procedure may be represented using the following autoregressive system:

$$(6.11) \quad z_t = \sum_{i=1}^{k} \alpha_i z_{t-i} + \sum_{i=1}^{k} \beta_i x_{t-i} + \mu_t$$

$$(6.12) \quad x_t = \sum_{i=1}^{k} \gamma_i x_{t-i} + \sum_{i=1}^{k} \delta_i z_{t-i} + v_t$$

where μ_t e v_t are white noise error terms.

By definition, x_t fails to Granger cause z_t if coefficients β_i in equation (6.11) are zero. This is tested by a joint significance test of all β_i. One may also test the direction of causality from z_t to x_t using the same procedure. In this case, one tests the joint significance of coefficients δ_i in equation (6.12). Such tests are based on the assumption that x_t and z_t are stationary. Since the original series are likely to be non stationary, commonly the series are differentiated before running the tests. However, in such a transformation, the long-run components of the series may be removed. Therefore, the standard Granger causality test only indicates short-run causality. Thus, in order to take into account a possible common long-run pattern in the two time series, we also consider the existence of cointegration between the two variables and use causality tests that incorporate long-run effects.

In the following section we first analyse the property of each time series and perform the standard Granger causality tests. In section three we move on to the use of cointegration techniques. The time series used in the following analysis refer to annual R&D expenditure in the industrial sector, excluding federal funds, and annual aggregate investment in machinery and equipment for the US economy over the period 1953-1993. Both series are deflated using the GDP deflator (1980=100) and summary statistics and sources are reported in the Appendix.

6.3.1 Unit Root Tests

A time series, z_t, is stationary (weakly) if its mean and its autocovariance function do not depend on the date t, that is:

$$E(z_t) = \mu$$
$$\mathrm{cov}[z_t, z_{t+k}] = \phi(k)$$

If a time series satisfies these properties, it is said to be integrated of order zero *(I(0))*. If a first differentiation is needed to achieve stationarity, the series is said to be integrated of order one *(I(1))*. Higher order differentiations imply a higher order of integration.

During recent years, a huge literature on testing procedures for non stationarity (i.e., unit root tests) has developed. The drawback of these tests lies, as is well known, in the weak power usually shown under certain circumstances. Keeping this point in mind, we have tested for unit roots each time series using the *ADF* test (Dikey and Fuller (1981)) and the Phillips and Perron test (Phillips and Perron 1988). The latter may be preferred in the presence of autocorrelation. It has been shown (Schwert 1987) that if the error term is characterised by a moving average representation *(MA(1))* both procedures may give biased results but in this case the *ADF* test seems to perform better than the Phillips and Perron test. We have also analysed each time series using the typical visual inspection suggested in Box and Jenkins (1970). This makes it possible to check if there are any discrepancies between the unit root testing procedure and the correlograms of the time series.

We first tested for a unit root using the *ADF* test in its more general form, which allows one to discriminate between different parameter restrictions. The data generating mechanism is assumed to be:

$$(6.13)\quad z_t = \alpha + \rho z_{t-1} + \beta t + \sum_{i=1}^{k} \phi_i \Delta z_{t-i} + \varepsilon_t$$

where t is a time trend and ε_t is a white noise error term. Furthermore, lagged differentiated values of z_t are added to account for autocorrelation. We therefore test the hypothesis that $\rho=1$ in equation (6.13). Four test statistics are calculated:

$$k(1) = T(\hat{\rho} - 1);\quad t(1) = \frac{\hat{\rho} - 1}{SE(\hat{\rho})};\quad F(0,0,1);\quad F(0,1)$$

where $\hat{\rho}$ is the OLS estimate of ρ from (6.13), $SE(\hat{\rho})$ is the standard error of $\hat{\rho}$, $F(0,0,1)$ is the F statistic for testing the joint hypothesis $\alpha=\beta=0$ and $\rho=1$, $F(0,1)$ is the F statistic for testing the joint hypothesis $\beta=0$ and $\rho=1$ in (6.13). The following table summarises the results of the test procedures:

Tab. 6.1 ***ADF* tests***

	lmaceqr	*lrrdusa*
k(1)	-10.1967	-9.646
t(1)	-2.2120	-2.744
F(0,0,1)	4.73	10.79
F(0,1)	2.92	5.05

lmacqrr= natural log of real investment in machinery and equipment
lrrdusa= natural log of real R&D expenditure
*The test involves the estimation of the following equation:

$$z_t = \alpha + \rho z_{t-1} + \beta t + \sum_{i=1}^{k} \phi_i \Delta z_{t-i} + \varepsilon_t$$

k, the number of lags on the differentiated term, is set equal to one, sufficient to get a white noise error term (ε_t). The modified LM test for joint 3rd order aoutocorrelation and the Box-Pierce test give the following results: LM(3)=1.116; Q(12)=6.75 in the *lmaceqr* regression and LM(3)=0.9058; Q(12)=8.87 in the *lrrdusa* regression.
Critical values (0.05 significance level) are as follows: k-test-22.5, t-test -4.38, F(0,0,1) test 5.68, F(0,1) test 10.61.

From Table 6.1, the unit root hypothesis cannot be rejected according to conventionally used critical values (Fuller (1976) and Dickey and Fuller (1981))[1]. Moreover, the *F(0,0,1)* and *F(0,1)* tests suggest the inclusion of a drift term in the data generating mechanism[2].

A test on the differentiated series rejects the unit root hypothesis for these series and thus the hypothesis that the series are *I(2)*.

6.3.2 Choosing the Appropriate Lag Length

Granger causality tests are crucially affected by the choice of an appropriate lag length. In order to determine the optimal lag length in a bivariate *VAR* we apply the Final Prediction Error criteria *(FPE)*, the *AIC* (Akaike 1974) criteria and the likelihood ratio test *(LR)* (Sims 1980). These criteria are applied to the differentiated *VAR* representation, with the results given in Table 6.2

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[1] This result is also confirmed by the Phillips and Perron tests for the same dynamic representation used for the ADF tests.

Phillips and Perron test for a unit root

	lmaceqr	*lrrdusa*
Z_p	-9.229	-8.622
Z_t	-2.047	-2.393

[2] Once the hypothesis of a unit root was not rejected, we have also tested for the significance of the trend and drift terms.

Significance of the trend and drift terms*

	lmaceqr	*lrrdusa*
trend	-0.606	-1.411
drift	3.164	7.451

* Trend refers to the t-statistic of the coefficient on the TREND variable in the regression of Δz_t on a constant and a linear trend. Drift refers to the t statistic of the coefficient on the constant term in the regression of Δz_t on a constant. The error terms of these equations are again tested for autocorrelation, providing evidence that the hypothesis of white noise error cannot be rejected.

Table 6.2 Optimal lag selection*

Lags					
	Δlmaceqr		*Δlrrdusa*		
	AIC	FPE	AIC	FPE	LR[♣]
3	-66.4577	$4.41x(10)^{-3}$	-116.680	$1.09x(10)^{-4}$	$\chi^2(4)=6.285$
2	-65.6322	$4.49x(10)^{-3}$	-116.880	$1.08x(10)^{-3}$	

* We do nor show the value of the statistics for other lag lengths as they exceed the values of the two and three lag selections.
[♣]The statistic is $(T-c)(\ln|\Sigma_r|-\ln|\Sigma_u|)$ where Σ_r and Σ_u are the restricted and unrestricted residual covariance matrices. T is the number of observations and c is a correction to improve small sample properties (see Sims (1980)).

These results of the two and three lag specifications are similar, according to the *AIC* and *FPE* criteria while the *LR* test suggests the choice of the two lag specification. Therefore, we proceed by first performing the Granger causality test using a two lag specification and then compare the results using a three lag specification. In addition we also employ the Hsiao (Hsiao 1979) version of the Granger causality test and compare the results.

Traditional Granger causality tests (Granger (1969)) are based on the OLS regression equations (6.11) and (6.12), after the selection of appropriate lags and the use of a filtering procedure to achieve stationarity. Table 6.3 shows *F* tests relating to the regressions of *Δlmaceqr* and *Δlrrdusa* on their own lagged values and lagged values of the other variable[3].

[3] The optimal lag selection must guarantee that the error term is white noise. Therefore, we have also tested for autocorrelation to check this assumption. The applied LM and Box Pierce tests show that the hypotesis of uncorrelated errors cannot be rejected.

Table 6.3 Causality tests

Three lag specification		*Two lag specification*	
R&D→Investment	*Investment→R&D*	*R&D→Investment*	*Investment→R&D*
$F_{3,29}$=5.45	$F_{3,29}$=1.099	$F_{2,31}$=5.94	$F_{2,31}$=0.04
Critical value = 2.94 (0.05 significance level)			

The sample period for the test is 1958-1993, corresponding to the sample size used for the lag selection tests.

The test statistics suggest that there is strong evidence of temporal precedence of R&D in the investment equation. In other words, R&D Granger causes investment. The value of the *F* test is far above its critical value. A feed-back relationship of investment on R&D is rejected in both specifications, particularly in the two lag representation where the value of the test statistic is close to zero.

The Hsiao version of Granger causality is based on the analysis of the *FPE* of equations (6.11) and (6.12). It is known also as a stepwise Granger causality procedure and it allows for the selection of an optimal lag structure. In a first step the lag length of the autoregressive specification of each time series is selected using the *FPE* criteria. Then one can add unit lags to the other variable and calculate the *FPE* (after each additional lag) in order to select the specification with the minimum value. The comparison of the *FPE* in the first step with the *FPE* in the second step makes it possible to detect Granger causality. In the two variable case, suppose that the autoregressive process of z_t may be expressed as

$$(6.14) \quad z_t = \sum_{i=1}^{k} a_{1i} z_{t-i} + \mu_{1t}$$

where μ_{1t} is a white noise error term and k is selected to minimise the *FPE*. Denote the *FPE* in (6.14) as $FPE^z(k,0)$. In the second step, we add unit lags of the second variable (x_t) and, for each additional lag, calculate the *FPE* in order to select the specification which minimises it. We thus have:

$$(6.15) \quad z_t = \sum_{i=1}^{k} \alpha_{2i} z_{t-i} + \sum_{i=1}^{n} \beta_i x_{t-i} + \mu_{2t}$$
$$n \leq k$$

Denoting $FPE^z(k,n)$ as the corresponding *FPE*, if $FPE^z(k,n) \leq FPE^z(k,0)$, then x_t causes z_t. Applying the same procedure to the opposite relationship gives the test for the other direction of causality.

The results of the *FPE* of a one-dimensional autoregressive process are shown in Table 6.4.

Table 6.4 *FPE* of a one dimensional autoregressive process of the R&D and Investment variables.

Lags	*Δlmaceqr*	*Δlrrdusa*
	$(x10)^{-3}$	$(x10)^{-3}$
2	6.66	0.97
3	6.81	1.02
4	6.16	1.06

The optimal lag length is two for both series. Given this choice, one has to choose the optimal lag in the regression for the causality test. Each controlled variable (alternatively *Δlmaceqr* and *Δlrrdusa*) enters the regression equation with two lags and the other variable (manipulated variable) enters the equation with the lag length suggested by the *FPE* criteria. In the investment equation the manipulated variable enters with two lags, whereas in the R&D equation the manipulated variable enters with just one lag. Table 6.5 summarises the results of applying Hsiao causality tests with their lag structure.

Table 6.5 Hsiao causality tests

$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{1i} \Delta lmaceqr_{t-i} + \sum_{i=}^{2} \beta_i lrrdusa_{t-i} + \varepsilon_{1t}$
FPE=4.95x(10)$^{-3}$
$\Delta lrrdusa = \sum_{i=1}^{2} \gamma_{1i} \Delta lrrdusa + \delta\ \Delta lmaceqr + \varepsilon_{2t}$
FPE=1.02x(10)$^{-3}$
$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{2i} \Delta lmaceqr + \varepsilon_{3t}$
FPE=5.56x(10)$^{-3}$
$\Delta lrrdusa = \sum_{i=1}^{2} \gamma_{2i} \Delta lrrdusa + \varepsilon_{4t}$
FPE=0.97x(10)$^{-3}$

The Hsiao version of the Granger causality test suggests that R&D causes investment. The opposite relationship is not sufficiently significant to reduce the *FPE* in the R&D equation, thus indicating that there is no feedback from investment to R&D.

6.3.3 Cointegration and Granger Causality

An important issue in economic analysis and econometrics is the investigation of the short-run and long-run dynamics of economic variables. During recent years much literature has focused on non stationary variables and the appropriate test procedures to identify the characteristics of time series.

In the previous sections we used unit root tests to identify the properties of the investment and R&D variables. The theory and practice of cointegration is based again on the concept of integrated variables. Recall that a time series is said to be integrated of order one, *I(1)*, if its first difference is stationary, i.e., is *I(0)*. A time series is said to be integrated of order 2, *I(2)*, if its first difference is integrated of order one.

Consider two time series, x_t and z_t, both integrated of order one. The two series are said to be cointegrated if there is a linear combination of the two series which is stationary, i.e., integrated of order zero, *I(0)*. If x_t and z_t are cointegrated there is a long-run relationship between them. In addition, one can use a vector autoregression to describe the short-run dynamics. The combination of the cointegrating regression and the vector autoregression describes a vector error correction model. This representation of the short-run and long-run dynamics is known as the Granger representation theorem (Engle and Granger (1987)). If x_t and z_t are cointegrated then they may be considered to be generated by an Error Correction Mechanism of the form:

$$(6.16)\quad \Delta x_t = \sum_{i=1}^{k} \gamma_1 \Delta x_{t-i} + \sum_{i=1}^{k} \gamma_2 \Delta z_{t-i} + \alpha_1 (z_{t-1} - \beta x_{t-1}) + \mu_{1t}$$

$$(6.17)\quad \Delta z_t = \sum_{i=1}^{k} \gamma_3 \Delta x_{t-i} + \sum_{i=1}^{k} \gamma_4 \Delta z_{t-i} + \alpha_2 (z_{t-1} - \beta x_{t-1}) + \mu_{2t}$$

The term $(z_{t-1}-\beta x_{t-1})$ represents the error correction term, i.e., the cointegrating equation and the parameters α_1 and α_2 reflect the speed of adjustment to past values disequilibrium. Engle and Granger suggest estimating first the cointegrating equation using a static OLS estimate. The second step involves the use of the residuals from the first step to estimate equations (6.16) and (6.17).

In a more general case with n variables and possible $n-1$ cointegrating vectors, Johansen (1988) derives a maximun likelihood approach to test for cointegration and then estimate the cointegrating equations. This approach enables to estimate simultaneously the cointegrating vector(s) and the parameters of the *VAR* system. To illustrate this procedure consider the system

$$(6.18)\quad \begin{aligned} &\Delta \mathbf{x}_t = \Gamma_1 \Delta \mathbf{x}_{t-1} + \dots\dots\dots\dots + \Gamma \Delta \mathbf{x}_{t-k+1} + \Pi \mathbf{x}_{t-k} + \mu_t \\ &\mu_t \quad \mathrm{IN}(0, \Sigma) \end{aligned}$$

where $\mathbf{x}_t$ is a $(nx1)$ vector of variables, Γ_i is a (nxn) matrix of coefficients, Π is (nxn) matrix of long-run coefficients and μ_t is a vector of disturbances indipendently and normally distributed. Furthermore, Π may be decomposed into a vector of coefficients which reflect the speed of adjustment to disequilibrium (α) and a vector of long-run coefficients which represent up to *(n-1)* cointegrating relationships (β),i.e., $\Pi=\alpha\beta'$. If $\mathbf{z}_t$ is a vector of non stationary *I(1)* variables then $\Delta\mathbf{z}_{t-i}$ and $\Pi\mathbf{z}_{t-k}$ must be stationary for μ_t to be stationary and white noise. For our analysis the relevant case in which $\Pi\mathbf{z}_{t-k}$ is *I(0)* is when there are up to *(n-1)* cointegrating vectors $\beta'\mathbf{z}_{t-k}$. Therefore, there are **r** columns of β which represent linear combinations of the variables in $\mathbf{z}_t$. Thus the problem is that of determining the number of $\mathbf{r}<(n-1)$ cointegrating vectors which can define the long-run relationships in system (6.18). Testing for cointegration in this framework implies the consideration of the rank of matrix Π, i.e., the number of **r** linearly independent columns in that matrix.

In a bivariate model the corresponding test statistic of the hypothesis of the existence of at most one cointegrating vector is:

$$(6.19)\quad LR = -T\ln(1-\hat{\lambda}_2)$$

and the test for the hypothesis of no cointegration takes the form:

$$(6.20)\quad LR = -T\left[\ln(1-\hat{\lambda}_1)+\ln(1-\hat{\lambda}_2)\right]$$

where $\hat{\lambda}_1$ and $\hat{\lambda}_2$ are the estimated characteristic roots of the matrix of long-run parameters and T is the number of observations.

Table 6.6 Johansen cointegration tests

	Null hypothesis (1)	*Null hypothesis (2)*
Lags	$r \leq 1$	$r=0$
2	2.71	19.56
3	1.96	10.41

The test is based on the hypothesis of no deterministic trend in the data.
The sample size is 1958-1993 as for the causality tests. r= number of cointegrating vectors
The 0.05 critical values are 3.84 and 12.53 respectively for hypothesis (1) and hypothesis (2).

Applying these tests to our data, Table 6.6 shows the results of the cointegration tests for two different lag specifications of the *VAR* model. In the two lag specification the existence of one cointegrating vector cannot be rejected. The second test rejects the hypothesis of no cointegration (equation 6.20). In a three-lag specification the evidence of cointegration is not as strong as with two lags. The hypothesis of the existence of one cointegrating vector is still not rejected, but the second hypothesis (r=0) is rejected at a significance level close to the 0.10 level.

Given these results, we use the Granger representation theorem in a two lag *VAR* specification to perform causality tests; this is also consistent with the evidence of the lag selection procedure analysed in section 6.3. The following equations are then considered:

$$(6.21)\quad \Delta z_t = \sum_{i=1}^{k} \delta_{1i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{2i} \Delta x_{t-i} + \delta_3 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{1t}$$

$$(6.22)\quad \Delta x_t = \sum_{i=1}^{k} \delta_{5i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{6i} \Delta z_{t-i} + \delta_7 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{2t}$$

where z_t=*lmaceqr* and x_t=*lrrdusa* and the term $(z_{t-1}-\delta_4 x_{t-1})$ represents the error correction term. Equation (5.21) may be used to test for causality from R&D to investment, whereas equation (6.22) tests the opposite causal relationship. Granger causality may arise in this framework from both a long-run effect and the short-run dynamics as incorporated in the differentiated terms. We substitute the Johansen estimate of the cointegrating relationship in equation (6.21) and (6.22) and then test for the significance of the coefficients. The results of this second Granger causality procedure are summarised in table (6.7)[4].

Table 6.7 Granger causality in the augmented *VAR* representation *(k=2)*

	R&D→Investment	
$\delta_3=0$	$\delta_{2i}=0$	$\delta_{2i}=0,\ \delta_3=0$
$F_1=10.654$	$F_2=5.115$	$F_3=6.606$
	Investment→R&D	
$\delta_7=0$	$\delta_{6i}=0$	$\delta_7=0,\ \delta_{6i}=0$
$F_4=13.313$	$F_5=0.444$	$F_6=4.469$

The F statistics are as follows: F_1 and F_4 (1, T-q-1); F_2 and F_5 (2, T-q-1); F_3 and F_6 (3, T-q-1), where T is the number of observations and q the number of coefficients in the unrestricted equation. Tests for residual autocorrelation in equations (8) and (9) are as follows: equation (8), LM(3)=1.63, Q(12)=8.46 . Equation (9), LM(3)= 0.948, Q(12)=10.02.
The sample size is 1958-1993 as in table 6.3 This corresponds to the sample size used for the lag selection tests and the traditional Granger causality tests.

[4] For an application of this procedure see also Agenor and Taylor (1993).

The results of this test procedure again show a clear temporal precedence of R&D in the investment regression. However, we also find a significant long-run feed back, given the significant impact of the error correction term in both equations[5], with investment causing R&D in the long-run.

In general our findings support the idea suggested by endogenous growth models, that R&D in the research sector promotes investment in new capital goods. A long-run feed-back is not neglected in our empirical findings, suggesting that research into new or improved capital goods is affected (in the longer run) by investment itself. This result partly reconciles our findings with those of Schmookler (1966) and could be rationalised on the grounds that, following Schmookler, successful investment affects profitability through an increase in market share or an increase in the size of the market. This may induce more innovative activity as expected profitability from investment increases. In addition, investment may affect R&D in the long-run as new plants require technical improvements and therefore more expenditure is needed to guarantee product development. Investment may also affect the long-run growth rate of the economy and have a positive impact on R&D through that route.

[5] The test on long-run causality may be implemented using the likelihood ratio test on coefficients δ_3 and δ_7 derived from the Johansen procedure. The results are as follows:

Long-run causality test

Null hypothesis	
$\delta_3=0$	$\chi(1)=9.05$
$\delta_7=0$	$\chi(1)=10.89$

6. 4 Causality Between R&D and Investment in an Intersectoral Framework

The time series analysis of the previous sections has revealed the controversy surrounding the causal relationship between R&D and investment. In this section we analyse this relationship within an intersectoral framework. We consider the problem of the casual relationship between R&D and investment at the industry level for 18 manufacturing sectors of the US economy for the period 1973- 1993. This analysis is complementary to the previous one and may help in understanding the dynamics and interaction between these variables.

The sectors we consider reflect the two digit ISIC classification and represent 18 manufacturing sectors over 21 years. The precise description of this classification is given in the Appendix. The R&D and investment variables are respectively sectoral business enterprise total intramural R&D expenditure (BERD) and total investment in machinery and equipment. Both variables are deflated by the 1980 GDP deflator.

We first describe the main facts which characterise the dynamics of R&D and investment at the industry level as they emerge from previous empirical investigations (Lach and Shankerman 1989,1992) and from the data set we have used. We then consider the time series properties of each variable in each sector and then test for causality using the whole panel data set.

It is worth analysing the time and cross sectional pattern of each variable to understand the reciprocal behaviour of R&D and investment over industries and time.

Lach and Schankerman find that the variablity of investment, both in levels and growth rate, is higher than the variability of R&D within US industries over the period 1958-1983 . The same pattern is observed within a sample of 191 firms in the scientific sectors. This finding, however, does not seem to be a stylised fact as it is not confirmed in other empirical investigation. In Toivanen and Stoneman (1997) it is shown that the variance of the log levels of R&D is twice as large that of investment, for a panel of 185 UK firms over the period from 1984 to 1992.

In our sample of US industries over the period from 1973 to 1993 we find that the volatility of R&D is higher than for investment, suggesting that the dynamic interaction between R&D and investment is more controversial than might be thought.

Table 6.8 presents a summary of the descriptive statistics of R&D and investment for the 21 years from 1973 to 1993. It is shown that R&D' s volatility, as measured by the coefficient of variation, is on average higher than investment's in contrast to Lach and Schankerman. The sectors where the latter is higher are: wood, petroleum, rubber, non-ferrous metals, office & computing equipment, radio, TV & communication equipment, motor vehicles.

Table 6. 8 Descriptive statistics

	Mean	*Median*	*Max*	*Min*	*S.D.*	*C.V.*
TOTMAN 3000	50267.57	51511.63	59158.92	36164.17	5821.524	0.115811
TOTMANRD	49515.19	52100.56	63152.55	34069.78	10794.82	0.21801
FOOD 3100	4555.742	4703.204	5144.308	3284.492	462.2217	0.101459
FOODRD	718.2563	695.5771	995.2536	467.4753	181.923	0.253284
TEX 3200	1824.588	1817.178	2154.905	1563.513	150.1863	0.082312
TEXRD	146.3493	126.2407	205.3117	101.6098	39.37955	0.269079
WOOD 3300	1220.777	1189.422	1733.672	832.8552	251.346	0.20589

	Mean	*Median*	*Max*	*Min*	*S.D.*	*C.V.*
WOODRD	137.5604	137.9311	176.7625	102.6189	18.51582	0.134601
PAPER 3400	6524.815	6563.401	9651.65	3788.462	1411.265	0.216292
PAPERRD	533.9721	480.8158	892.3164	337.1384	164.8355	0.308697
CHEM 3510+3520-3522	6265.069	6460	8754.135	4205.541	1364.835	0.217848
CHEMRD	3633.605	3593.896	5610.842	2464.238	932.0919	0.25652
DRUGS 3522	814.2413	730.6716	1672.865	295.4305	370.6902	0.455258
DRUGSRD	2732.759	2451.017	5556.173	1213.003	1373.863	0.502738
PETRO 3530+3540	2301.858	2201.115	3768.735	1094.831	742.4605	0.322548
PETRORD	1443.655	1448.656	1899.793	865.4376	305.3801	0.211533
RUBBER 3550+3560	1987.455	1948.886	2728.809	1228.251	438.4426	0.220605
RUBBERRD	669.1212	656	916.196	454.669	107.4457	0.160577
NMET 3600	1805.036	1708.958	2534.748	1219.839	382.5129	0.211914
NMETRD	452.7274	406	745.2975	325.5681	130.2932	0.287796
IRON 3710	2551.359	2311.309	3665.714	1233.008	839.0238	0.328854
IRONRD	305.6026	288.7867	536.1821	142.06	127.8518	0.41836
NONFER 3720	1093.476	1096.475	1374.073	816.7785	168.3266	0.153937
NONFERRD	303.3519	304.8397	376.5852	201.6722	43.1897	0.142375
METAL 3810	2172.717	2097.687	2655.927	1752.326	266.8368	0.122812
METALRD	586.7074	586.5005	843.1145	459.1241	93.97976	0.160182
OFFICE 3825	1276.663	1278.166	2285.51	399.7001	534.0123	0.418288
OFFICERD	5435.072	5581.973	8154.875	3011.654	1908.903	0.351219
ELECT 3830-3832	1367.793	1384.392	1623.066	1103.193	138.1217	0.100981
ELECTRD	1972.35	2368.169	3266.001	602.5717	1124.338	0.57005
RADIO 3832	3148.459	3356.743	5273.438	1277.381	1137.881	0.361409
RADIORD	7254.025	7103.3	10942.77	4331.483	2177.408	0.300165
MOTOR 3843	4174.089	4351.396	7691.121	1850.789	1274.947	0.305443
MOTORRD	5417.564	4955	7728.546	3396.672	1400.409	0.258494
PROFG 3850	1508.629	1431.361	2369.035	764.6437	567.3095	0.376043
PROFGRD	3511.639	3588.849	6249.252	1670.051	1374.215	0.391332
OTHER 3900	396.3003	387.5582	519.5179	290.3138	55.4266	0.13986
OTHERRD	318.0727	296.6721	455.5298	274.5766	54.56425	0.171546

The first row for each sector refers to investment, the second row to R&D. Isic classification code are indicated, according to the OECD ANBERD adjustment.
Millions of 1980 dollars.

In addition, R&D volatility is higher if one considers its cross-section measure. Cross-sectional variability is also informative because it neutralises cyclical fluctuations. Figure 6.1 plots the cross-sectional coefficient of variation against time, showing again that R&D variability is higher than investment variability.

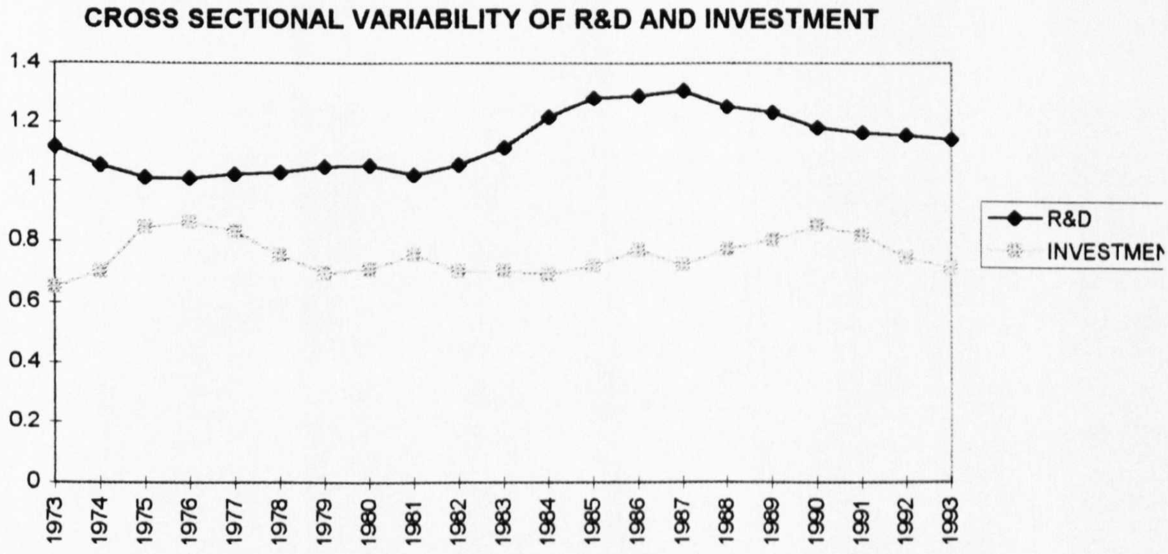


Figure 6.1 *Cross sectional variability of R&D and Investment*

Investment volatility, however, is higher, taking into account the standard deviation of growth rates of each variable. This is true in 15 sectors out of 18. The exceptions are food industries, electrical equipment and office and computing equipment. This empirical finding suggests that, contrary to Lach and Scankerman' s conclusions, the dynamic pattern of investment and R&D is not systematic, as it crucially depends on the time period and the economic structure taken into account for the empirical investigation.

Table 6.9 Investment and R&D growth rate by sector

	GRCHEM INV	GRCHEM RD	GRDRUGS INV	GRDRUGSRD	GRELECT INV	GRELECT RD	GRFOOD INV	GRFOOD RD
Mean	0.020823	0.041141	0.086693	0.076091	0.000251	-0.08328	0.019253	0.0276
Median	0.028794	0.028771	0.094107	0.0688	0.022374	-0.04453	0.028192	0.0260
Maximum	0.368418	0.13946	0.364271	0.211312	0.210883	0.056138	0.110888	0.2326
Minimum	-0.30621	-0.02235	-0.08852	-0.04098	-0.22972	-0.45713	-0.17183	-0.1569
Std. Dev.	0.154522	0.041608	0.119676	0.057351	0.1167	0.137797	0.064532	0.0856

	GRIRON INV	GRIRON RD	GRMETAL INV	GRMETAL RD	GRMOTOR INV	GRMOTORRD	GRNMET INV	GRNMET RD
Mean	-0.01976	-0.02392	-0.00282	0.025557	0.023525	0.025569	-0.02072	0.0053
Median	0.01168	0.025099	-0.00518	0.025325	0.060699	0.05304	-0.04816	0.0286
Maximum	0.342327	0.211661	0.232268	0.253	0.61747	0.310004	0.310002	0.1648
Minimum	-0.49701	-0.55187	-0.21878	-0.16649	-0.79093	-0.11527	-0.33717	-0.3388
Std. Dev.	0.206331	0.174357	0.119922	0.090293	0.375963	0.110943	0.175492	0.1280

	GRNONFER INV	GRNONFER RD	GROFFICE INV	GROFFICE RD	GROTHER INV	GROTHER RD	GRPAPER INV	GRPAP RD
Mean	0.001298	-0.00439	0.054061	-0.00151	0.006776	0.000874	0.025446	0.0486
Median	0.016944	0.038183	0.049845	0.025527	-0.05209	0.016483	0.046859	0.0436
Maximum	0.483249	0.188372	0.42502	0.191759	0.581939	0.137187	0.207409	0.25171
Minimum	-0.29442	-0.43348	-0.39111	-0.88684	-0.23431	-0.39312	-0.20438	-0.0843
Std. Dev.	0.177167	0.167857	0.187629	0.223816	0.184958	0.108708	0.112242	0.0939

	GRPETRO INV	GRPETRO RD	GRRADIO INV	GRRADIO RD	GRRUBBER INV	GRRUBBER RD	GRTEX INV	GRTEX RD
Mean	0.055782	0.0198	0.045135	0.014345	0.020362	0.00249	-0.00764	0.0306
Median	0.033664	0.025633	0.0915	0.027981	0.018234	0.011537	-0.01205	0.03017
Maximum	0.462769	0.140016	0.324806	0.170865	0.44395	0.229624	0.17136	0.1574
Minimum	-0.31351	-0.11915	-0.33571	-0.14794	-0.30219	-0.20476	-0.22238	-0.0801
Std. Dev.	0.221408	0.082504	0.183212	0.093	0.17572	0.116527	0.11095	0.07367

	GRWOOD INV	GRWOOD RD	GRTOTMAN INV	GRTOTMAN RD
Mean	-0.0204	0.017975	0.018523	0.019697
Median	-0.05446	-0.00041	0.017774	0.024635
Maximum	0.295859	0.224373	0.179762	0.084699
Minimum	-0.28295	-0.15452	-0.20343	-0.06539
Std. Dev.	0.160079	0.106301	0.09991	0.045846

Table 6.10 **R&D - INVESTMENT RATIO (at sample mean)**

	ISIC code	
TOTMAN	3000	0.985032
FOOD	3100	0.15766
TEX	3200	0.08021
WOOD	3300	0.112683
PAPER	3400	0.081837
CHEM	3510+3520-3522	0.579978
DRUGS	3522	3.356203
PETRO	3530-3540	0.627169
RUBBER	3550+3560	0.336672
NMET	3600	0.250814
IRON	3710	0.11978
NONFER	3720	0.27742
METAL	3810	0.270034
OFFICE	3825	4.257249
ELECT	3830-3832	1.441995
RADIO	3832	2.303992
MOTOR	3843	1.297903
PROFG	3850	2.327702
OTHER	3900	0.802605

To conclude the description of the data, we have also considered the ratio of R&D expenditure to investment in each sector. Over all manufacturing industries, on average, the levels of R&D and investment are quite similar. The ratio of R&D to investment expenditure is about 0.99. However, this ratio is not uniformly distributed across industries as R&D expenditure is even higher than investment in high tech industries, while is less considerable in traditional sectors. Nevertheless, it appears that R&D activity is quite significant in the US manufacturing sector when compared to machinery and equipment investment.

6. 4.1 Time Series Properties of the Variables

In the previous sections we analysed Granger causality in a pure time series framework.. We now want to perform the same test for the panel of industries we described above. However, we need to analyse the dynamic properties of each variable and then perform Granger causality tests. A key question, as we have already underlined, is whether each variable is stationary or non-stationary. Therefore, for each variable we perform a unit root test in each sector, by calculating the augmented Dickey-Fuller statistic, including a constant, a time trend and augmenting with one lag of the variable to take autocorrelation into account.

Table 6.11a shows the results of this procedure. A unit root cannot be rejected for the R&D variable in all sectors while for the investment variable this hypothesis cannot be rejected at the 0.05 significance level for 14 sectors out of 18.

Table 6.11a Unit root test for the R&D and investment variables in each sector

	R&D			**INVESTMENT**		
	Reject	*Cannot*	*t-value*	*Reject*	*Cannot*	*t-value*
TOTAL MANUF		yes	-0.134		yes	-2.559
FOOD		yes	-0.208	yes**		-3.245
TEXTILE		yes	-2.206	yes		-6.889
WOOD		yes	-1.138	yes**		-3.312
PAPER		yes	-1.304		yes	-2.446
CHEM		yes	-2.847		yes	-2.198
DRUGS		yes	-2.43		yes	-3.017

	R&D			INVESTMENT		
	Reject	*Cannot*	*t-value*	*Reject*	*Cannot*	*t-value*
PETRO		yes	-0.816		yes	-2.202
RUBBER		yes	-1.724		yes	-0.262
NMET		yes	-2.122		yes	-2.685
IRON		yes	-2.036		yes	-2.02
NONFER		yes	-2.869		yes	-2.991
METAL		yes	-2.417		yes	-3.002
OFFICE		yes	-0.469		yes	-1.203
ELECT		yes	-2.004		yes	-2.398
RADIO		yes	-1.118		yes	-1.685
MOTOR		yes	-2.742	yes**		-3.524
PROFG		yes	-2.985		yes	-1.911
OTHER		yes	-2.192		yes	-2.309

0.05 c.v. -3.0294
0.10 c.v. -2.655

** Rejection at the 0.05 sig. level

However, it is well known that in small samples this test is of low power and therefore we perform a new unit root test which take as our null hypothesis the joint hypothesis that the variables are non-stationary in every sector. This procedure is suggested in Im, Pesaran and Shin (1995). The argument used for their test is that if data on the variable in each sector is regarded as an independent draw from a non stationary distribution then the t value used for the Dickey-Fuller test has the same expected values and variance in each sector. As the number of sectors increases we expect the average t to be close to the expected t value, with an error that depends on the variance of the t statistic. The Im, Pesaran and Shin version of the Dickey-Fuller test can therefore be computed by taking the difference between the average and expected t and adjusting for the variance of t. Using Monte Carlo simulations the values of expexted t and its variance were tabulated. Average t can easily be computed from our previous unit root tests in each sector and therefore the unit root test for heterogeneous panels can be computed. Formally the test is

$$(6.23)\quad \dot{z}_{NT} = \frac{\sqrt{N}\left[\bar{t}_{NT} - E(t_T)\right]}{\sqrt{V(t_T)}}$$

where N is the number of groups (sectors) and T the number of time periods. $\bar{t}$ is the average t value obtained from the unit root test in each sector, $E(t_T)$ is the expected t tabulated via stochastic simulations for different values of T and under different assumptions on the data generating mechanism and $V(t_T)$ is its variance. $\bar{z}_{NT}$ follows a normal standard distribution.

Table 6.11b Unit Root Test for panel data

Variable	*No. of sectors*	*Average t*	*Expected t*	*Variance t*	*Test N(0,1)*
R&D	18	-1.868	-2.167	0.844	1.381
Investment	18	2.627	-2.167	0.844	-2.124

As shown in Im, Pesaran and Shin, the test is distributed according to the standard normal distribution and, therefore, the critical value for a two tails test at the 0.05 significance level is ± 1.96.

We cannot reject the null hypothesis of a unit root for the R&D variable, while for the investment variable the value of the test is slightly higher than the assigned critical value. This result is expected, as it confirms the unit root tests of table 6.11 where the hypothesis has been tested in each sector separately showing that for four sectors out of 18 we could not reject the null hypothesis only for significance levels higher than the assigned 0.05 level.

However, given that the investment variable is difference stationary in almost all sectors, we have estimated the following vector autoregression for testing causality:

$$\Delta y_{it} = \alpha_{1i} + \gamma_{1t} + \sum_{n=1}^{p} \beta_{1n} \Delta y_{i,t-n} + \sum_{n=1}^{p} \delta_{1n} \Delta x_{i,t-n} + \mu_{it}$$
$$\Delta x_{it} = \alpha_{2i} + \gamma_{2t} + \sum_{n=1}^{p} \beta_{2n} \Delta y_{i,t-n} + \sum_{n=1}^{p} \delta_{2n} \Delta x_{i,t-n} + \upsilon_{it}$$

where y_{it} and x_{it} are respectively the R&D and investment variables, α_{1i} and α_{2i} are sector specific intercepts and γ_{1t} and γ_{2t} are time specific dummies to capture common shocks. In both cases we have tested whether the correct specification is one with individual and time fixed effects. The tests suggest that the correct specification is one with both individual and time fixed effects, as shown in Table 6.12.

Table 6.12 Model selection tests

Number of lags		*Investment*	
2	AIC=0.0246	R^2 adj=0.255	χ_{34}^2 = 121.49 (*)
3	AIC=0.0243	R^2 adj=0.276	χ_{34}^2 = 122.88 (*)
Number of lags		*R&D*	
2	AIC= 0.0125	R^2 adj=0.129	χ_{34}^2 = 56.62 (*)
3	AIC= 0.0132	R^2 adj=0.125	χ_{34}^2 = 52.1 (*)

(*) The test is the difference between the log likelihood of the model without group and time dummies and the log likelihood of the model which includes both fixed effects.

In order to select the optimal lag length we have used the *AIC* information criteria. Furthermore, we have considered the adjusted R^2 of each equation to find confirmation of the selection criteria adopted. This allows us to discriminate between different lag specifications, suggesting that the two and three lag autoregressive models are more appropriate compared with others, as shown in table 6.12 It is worth noting that this choice also emerges from the time series analysis of section 6.3

Table 6.13 shows regressions for the causality test using the panel data which includes 18 sectors for the period 1973-1993. We have included industries and year dummies as suggested by tests reported in Table 6.12 . In addition we have calculated heteroskedastic consistent standard errors to take account of heteroskedasticity (White 1980). The results of the causality tests in this panel suggest that R&D causes investment only in the three lag specification at the 0.12 significance level, which is high compared with the corresponding level of the time series test. The reverse causal link does not hold. On the other hand, investment causes R&D in the two lag specification at the 0.20 significance level. This result strengthens the time series finding as R&D reduces the prediction error of the equation in which it enters (with some lags) more than investment does.

Table 6.13 Regressions for causality tests

	(1) Δlmaceqr	*(2)Δlmaceqr*		*(3)Δlrrdusa*	*(4)Δlrrdusa*
δ_{21}	-0.0240 (0.0884)	-0.0180 (0.0568)	δ_{11}	-0.0159 (0.0416)	-0.0164 (0.0360)
δ_{22}	-0.1344 (0.0651)	-0.1562 (0.0564)	δ_{12}	0.0775 (0.0446)	0.0712 (0.0425)
δ_{23}	-0.1071 (0.0599)	------------		-0.0322 (0.0369)	--------------
β_{21}	0.1291 (0.0891)	0.1008 (0.0869)	β_{11}	-0.1728 (0.0697)	0.1591 (0.0670)
β_{22}	-0.0223 (0.1022)	-0.0595 (0.0892)	β_{12}	0.0437 (0.0628)	0.0352 (0.0628)
β_{23}	-0.1767 (0.0787)	---------------		-0.0622 (0.0859)	--------------
R^2 *adj*	0.278	0.258		0.1285	0.132
N	306	324		306	324
F	1.93 (1)	0.77 (2)		0.90 (3)	1.59 (3)
	p-value= 0.125				p-value= 0.206

(1) $H_0: \beta_{21}=\beta_{22}=\beta_{23}=0$; (2) $H_0: \beta_{21}=\beta_{22}=\alpha_3=0$; (3) $H_0: \delta_{11}=\delta_{12}=\delta_{13}=0$; (4) $H_0: \delta_{11}=\delta_{12}=0$.
* Industry and year dummies are included in all regressions.
** Heteroskedastic consistent standard errors in parenthesis

6.4.2 Long-Run Relationship

In the previous sections we have described the implication of cointegration for a vector autoregression . If two variables are cointegrated, the vector autoregression is misspecified unless the cointegrating vector is added to the *VAR* specification. The theory of cointegration, however, is not well suited for panel data and therefore a specific cointegration test is not yet available for empirical research. However, we decided to test whether R&D and investment are cointegrated in each sector and found that in 10 sectors out of 18 the hypothesis of cointegrated variables cannot be rejected for a significance level between 0.05 and 0.15. We used the Engle and Granger test for cointegration, i.e., we tested for a unit root in the OLS residuals of the regression between investment and R&D.

In the other 8 sectors the hypothesis of cointegration cannot be rejected for higher significance levels.

However, given the limitations of unit root tests and the evidence of cointegration (although not as strong as at the economy wide level) in the majority of industries, we decided for this panel to also use the augmented *VAR* specification which includes an error correction term. This latter is obtained by regressing one period lagged investment on one period lagged R&D, including industries and time dummies.

Table 6.14 **Cointegration test for R&D and Investment in each sector**

		t values
TOTAL MANUF		-2.481
FOOD		-2.610
TEXTILE*		————
WOOD		————
PAPER		-1.647
CHEM		-2.434
DRUGS		-2.495
PETRO		-1.970
RUBBER		-1.290
NMET		-1.534
IRON		-1.749
NONFER		-1.790
METAL		-3.129
OFFICE		-1.983
ELECT		-2.530
RADIO		-1.827
MOTOR		-3.415
PROFG		-1.810
OTHER		-2.390
0.05 c.v.	-3.0294	
0.10 c.v.	-2.655	

* Investment is not I(1) in this sector according to the unit root test of Table 6.11a
§This is the Dickey Fuller test applied to the residual of the OLS rgression of investment and R&D.

Table 6.15 reports the results of the regressions for the causality tests. It is shown that R&D causes investment in the short-run and in the long-run. As in the unconditional *VAR* specification of Table 6.13, lagged values of R&D are significant in the investment equation at the 0.11 significance level. The error correction term is highly significant. Investment has a significant feed-back on R&D in the long-run as is shown in the two- and three-lag specification. Lagged values of investment are significant only at the 0.31 significance level in the three-lag specification of the R&D equation. These findings reinforce the results of the time series analysis of section 6.3 and clearly underline how the causal link from R&D to investment is a stylised fact of the US economy.

Table 6.15 Regression for causality test

	(1) Δlmaceqr	*(3)Δlmaceqr*		*(2)Δlrrdusa*	*(4)Δlrrdusa*
δ_{21}	0.1209 (0.0765)	0.1067 (0.0718)	δ_{11}	-0.0498 (0.0431)	-0.0409 (0.0431)
δ_{22}	-0.0043 (0.0624)	-0.0311 (0.0624)	δ_{12}	0.0472 (0.0459)	0.0466 (0.0428)
δ_{23}	-0.0054 (0.0591)	------------------		-0.0558 (0.0371)	-----------------
β_{21}	0.1388 (0.0799)	0.1354 (0.0805)	β_{11}	0.1706 (0.0695)	0.1523 (0.0619)
β_{22}	0.0139 (0.1015)	-0.0188 (0.1015)	β_{12}	0.0352 (0.0626)	0.02717 (0.0636)
β_{23}	-0.1600 (0.0691)	-------------------		-0.0661 (0.0836)	------------------
EC	-0.2862 (0.0463)		EC	0.0668 (0.0320)	0.0519 (0.0319)
R2	0.3682	0.346		0.305	
N	306	324		306	324
F(1)	11.36$^{(1)}$	13.80$^{(2)}$		1.82$^{(3)}$	1.89$^{(4)}$
F(2)	2.02$^{(5)}$	1.35$^{(6)}$		1.21$^{(7)}$	0.99$^{(8)}$
F(3)	38.61$^{(9)}$	39.6$^{(9)}$		3.29$^{(9}$	2.34$^{(9)}$

(1) $H_0 : \beta_{21}=\beta_{22}=\beta_{23}=EC=0$ (2)$H_0 : \beta_{21}=\beta_{22}=EC=0$; (3) $H_0= \delta_{21},=\delta_{22}= \delta_{23} =EC=0$ (4)$H_0 : \delta_{11}=\delta_{12}=EC=0$; (5) $H_0 : \beta_{21}=\beta_{22}=\beta_{23}=0$ (6) $H_0 : \beta_{21}=\beta_{22}=0$; (7) $H_0= \delta_{21},=\delta_{22}= \delta_{23} =0$ (8) $H_0 : \delta_{11}=\delta_{12}=0$; (9) $H_0=EC=0$.
Industry and years dummies are included in all regressions.
Hesteroskedastic standard errors in parenthesis.

The results of this section confirm the time series findings of section 6.3 . R&D Granger causes investment in the short-run and has a significant effect also in the long-run. Investment has a significant-feed back on R&D in the long-run, while the effect in the short-run is not as strong as the opposite effect. This finding suggests that our results for the US economy are robust and give important insights into the understanding of the dynamics of such crucial variables and represents an important test for the theoretical implications of endogenous growth models.

6. 5 Conclusions

In this chapter we first explored the causal relationship between R&D and investment in machinery and equipment. Interest in this issue derives, on the one hand, from the existing empirical literature originating in the pioneer work by Schmookler and, on the other hand, from the emphasis that the endogenous growth theory places on the R&D sector as a producer of new designs needed for the production of capital goods. This link becomes crucial in the overall growth process of the economy.

We first analyse the relationship between R&D and investment using the standard Granger causality approach. The results show a clear direction of causality from R&D to investment. A feed-back relationship is rejected. The Hsiao version of Granger causality confirms these results. We then perform Granger causality tests in a cointegrating framework. This procedure allows for an augmented version of the standard causality test. Together with the usual differentiated *VAR* specification, one can include an error correction term indicating any long-run relationship. In this case, the results again show short-run causality running from R&D to investment. However, given that the error correction term is significant in both equations, there is also evidence of long-run feedback.

The interaction between R&D and investment has also been analysed in an intersectoral framework, covering 18 manufacturing industries of the US economy for the period 1973-1993. We consider the problem of stationarity within a panel data set and, after the appropriate test procedure, we specify a vector autoregression suitable for testing causality.

The results again suggest the crucial role played by R&D expenditure in determining investment. We also specify a long-run model, after testing for cointegration between R&D and investment in each sector. The results of this intesectoral investigation confirm the long-run feed back between the two variables and the short-run effect running from R&D to investment, thus reinforcing our previous results based on time series data for the US economy.

In chapter 7 these findings are compared with those obtained for the UK economy, thus giving a more detailed picture of the relationship between these variables.

Appendix I

A.1 Data description

The use of aggregate data is consistent with the specification of the theoretical models. The use of private R&D data is also more appropriate for testing the predictions of the R&D endogenous growth models, which consider the output of research activity carried out by private profit-maximising firms. The exclusion of Federal funds depends on their responsiveness to a variety of factors which are not accounted for by the theoretical models, while private R&D reflects the attitude of firms towards one (important) kind of innovative activity.

Federal R&D funds represent a large proportion of total R&D, particularly in the US economy, but they crucially depend on exogenous factors like fiscal policy aimed at reducing the budget deficit, or changing domestic concerns such as national security issues.

The distinction between defence and civil R&D is also crucial when considering government-financed R&D, as the former plays a very important role in the US economy. In addition, civil R&D must be subdivided between funds devoted directly to R&D and those devoted to research centres or universities.

The share of government-financed defence R&D is particularly high in the US (almost 59%), though in the last years more attention has been paid to rationalising the R&D activities within the R&D defence projects.

It is worth underlining that this macro-level approach allows us to take into account spill-over effects. Indeed, the relationship between R&D and investment can also be influenced by such effects, in that the R&D activity carried out by one firm may impact on the investment decision of another firm if spill-over effects are significant. Thus one has to take this issue into account when comparing other results from the empirical literature based on micro data reflecting the R&D propensity and the investment decisions of individual firms.

A limitation of this aggregate analysis is its inability to discriminate between the different aims of R&D activity, i.e., producing new products, improving the quality of existing products or introducing new or improved processes, and then split off the R&D effort mainly devoted to the creation of new capital goods.

Together with economy-wide data, we also present sectoral data on R&D and investment in machinery and equipment. This analysis enables us to take into account industry diversity and thus to obtain a more realistic representation of the relationship between R&D and investment.

As is clearly shown in table 6.8 sectoral differences in research intensity vary substantially, suggesting that technological opportunities differ from sector to sector.

In our sample we do not consider the aerospace and other transport equipment sectors, as the time series component of the data set is too short for these sectors. However, the exclusion of the aerospace industry makes the sectoral comparison with the economy-wide investigation more consistent, as R&D in the aerospace industry is mostly supported by Federal funds.

In table (A.1) we give a sectoral breakdown of industrial R&D providing a more accurate description of the sectoral differences in R&D attitudes.

Tab. A.1 Breakdown of industrial R&D in US manufacturing
Engineering branch
Electrical/Electronics group
Machinery group
Aerospace group
Other transportation equipment group
Basic Metal group
Chemical branch
Chemicals group
Chemicals-linked group
Other manufacturing industries group

We consider four main industrial groups, which correspond to the most common international classification:

- Engineering branch

- Basic metal group;
- Chemicals branch;
- Other manufacturing industries group

Table (A.2) shows the composition of each group, corresponding to the two digit ISIC sectoral classification suggested by OECD:

Tab A.2 Composition of industry groups
Electrical/Electronics group
Electrical machinery, electronic equipment and component (excluding computers)
Machinery
Instruments, office equipment and computers, machinery n.e.c.
Aerospace group
Aerospace (including missiles)
Basic Metals group
Ferrous metals, non ferrous metals, fabricated metal products
Chemicals group
Chemicals, drugs, petroleum refining
Chemicals-linked group
Food and beverages, textiles and apparel, rubber and plastics products
Other manufacturing industries group
Stone, clay and glass, paper and printing, furniture, wood cork and other manufacturing industries

Overall we can distinguish between the "major" R&D performing industry groups, which each account for at least 10% of industrial R&D and the "minor" R&D performing industry groups, which each contribute 5% or less to total R&D.

In this latter group we find the basic metals group, chemical-linked, and other manufacturing industries. We now consider the contribution, within each group, of the main sectors to total R&D expenditure.

The electrical/electronics group includes industries producing electrical and electronic machines, appliances, equipment and components excluding data processing equipment (computers) which is included in the mechanical engineering group.

R&D in this group accounts for almost 19% of total R&D in manufacturing on average over the sample period, and the ratio of R&D to investment is near 2. The significant weight of R&D in this industrial group crucially depends on the inroads made by electronics in a wide number of industries.

The chemical group, which includes the chemicals, drugs and oil-refining industries, accounts for almost 16% of total R&D in manufacturing. Within this group the chemical industry component is 46.5 %, while oil refining represents 18.6% and drugs 34.9%. The R&D-investment ratio is higher in this group, particularly in the drugs industry where it is (greater than) 3.3.

The mechanical engineering group, which comprises non-electrical machinery, office equipment (including computers), precision instruments and appliances, spends about the same amount on R&D as the chemicals group.

Together with the electrical/electronics group and the drugs industry, it shows the highest R&D-investment ratio. This group represents the mainstream of technological change which began in the 1980s when technology was being ransferred from the electronics industry, thus reinforcing the role of R&D expenditure in this sector.

As we previously mentioned, we do not consider the aerospace industry because of the lack of time series data. However, it is worthwhile noting that there are anyway difficulties in using the ISIC classification for R&D analysis in this sector because R&D resources devoted to aeronautical engineering or the fabrication of missiles and rockets may be included in other sub-sectors for reasons dealing with national R&D surveys.

Other transport equipment includes the motor vehicles industry, shipbuilding and other transportation equipment. In the data set we used we do not have enough observations for these two latter sectors, and thus they were not considered in the econometric tests. The motor vehicle industry accounts on average for 11% of total R&D in manufacturing and its R&D-investment ratio is about 1.3.

The chemicals-linked group is a part of the "minor" R&D group in the US and in the OECD area. This group includes three industries: Food, beverages and tobacco, Textiles, apparel and leather; Rubber and plastics, and accounts for 3.1% of total R&D in manufacturing .

Within the "minor" R&D group we also find industries belonging to the basic metal group, which accounts for. 2.4% of total R&D in the US manufacturing sector. This group, after a period in the 1950s and 1960s when it played a key role in economic growth, had to restructure and diversify its products and activities. The ratio of R&D expenditure to investment is fairly low within this group of industries and varies between 0.11 (iron industry) and 0.28 (non ferrous metals).

R&D efforts within this group are fabricated metal products (49% of total R&D), non-ferrous metals (25.4%) and iron and steel (25.6%).

The sectoral breakdown we have so far described gives a general picture of the distribution of technological opportunities among sectors. However, it is worthwhile to note that sectoral differences may be described in more detail in the light of the so-called Sectoral Innovation Systems (SIS) (Breschi and Malerba (1997)), which enables one to gauge the intrinsic characteristics of sectoral patterns of technological opportunities.

Each SIS may be defined in terms of various technological regimes, which may be identified through the following factors:

i) opportunity conditions;

ii) appropriability conditions;

iii) cumulativeness of technological knowledge;

iv) nature of the relevant knowledge base.

The first element reflects the likelihood of innovating for any given amount of invested resources. The second element defines the possibility of protecting innovations from imitation and, therefore, gaining profits from innovative activity. Cumulativeness refers to the possible time dependence of the innovation process, reflecting the probability of innovating at time t, conditional on having introduced an innovation at time t-1. This implies that an environment characterised by cumulativeness is one in which there are significant continuities in innovative activities. The last element deals with the various degrees of specificity, tacitness, complexity and independence. In particular, knowledge may have a generic or specific nature and may be primarily local or codified, and may show different transferability conditions among agents. At the same time knowledge may show relatively high or low degrees of complexity and independence.

Given these definitions it is then possible to identify at least five types of SIS, with reference to:

a) traditional sectors which have many innovators, and geographically dispersed and with no specific knowledge spatial boundaries. Textiles, shoes and clothes, wood and paper products are typically included in this class. These are sectors characterised by a low degree of opportunity, appropriability and cumulativeness with relevant knowledge which is relatively simple, generic and embodied in equipment and materials. In this group one can also classify some traditional chemical-linked industries, e.g., rubber and plastics.

b) the mechanical engineering and machinery industries in which there is a combination of medium opportunity, low appropriability and high cumulativeness. Knowledge underlying the innovation process involves a high degree of tacitness and specificity, though it may be simple and codificable.

c) large-scale assembly industries (e.g., the motor vehicle industry) in which there is a combination of medium opportunity, high appropriability and high cumulativeness, together with a knowledge base which has a tacit component, though, geographically concentrated and with local boundaries.

d) high technology industries (e.g., the electronic and computer industries) which are characterised by high opportunity conditions and a relevant knowledge base which shows strong systematic features and high complexity. In this group we can also include the most technologically advanced sectors of the chemical group,

e) high technology industries such as microelectronics, biotechnology and the pharmaceutical industry, which are characterised by high opportunity conditions and a large variety of technological approaches and solutions. The source of technological opportunities is often related to the application of new scientific advance and the relevant knowledge base involves tacit as well as codified aspects.

Such a sectoral classification gives us a wider perspective on the distribution of technological opportunities among sectors, which in our case is proxied by R&D expenditures, and thus help us to understand the relative position of each sector within the manufacturing innovation system as a whole.

Appendix II

Table A1 Data Sources

RDUSA= R&D expenditure in the industrial sector excluding federal funds.

Source: National Science Foundation, R&D in Industry 1992-93.

MACEQ= Machinery and Equipment Investment.

Source: OECD, National Accounts (Annual Data 1953-1993)

The GDP deflator is calculated from the GDP statistics of **the OECD National Accounts, (Annual Data, 1953-1993)**.

LRRDUSA= natural log of real R&D expenditure (deflated by 1980 GDP deflator)

LMACEQR= natural log of real investment in machinery and equipment (deflated by 1980 GDP deflator)

Table A2 Sample Statistics (Mean, Standard Deviation)

Variable	*Mean*	*SD*
lmaceqr	11.667	0.514
lrrdusa	10.015	0.627

Table A3. Descriptive statistics of the variables used for the intesectoral analysis

	Mean	*Median*	*Max*	*Min*	*S.D.*	*C.V.*
TOTMAN 3000	50267.57	51511.63	59158.92	36164.17	5821.524	0.115811
TOTMANRD	49515.19	52100.56	63152.55	34069.78	10794.82	0.21801
FOOD 3100	4555.742	4703.204	5144.308	3284.492	462.2217	0.101459
FOODRD	718.2563	695.5771	995.2536	467.4753	181.923	0.253284
TEX 3200	1824.588	1817.178	2154.905	1563.513	150.1863	0.082312
TEXRD	146.3493	126.2407	205.3117	101.6098	39.37955	0.269079
WOOD 3300	1220.777	1189.422	1733.672	832.8552	251.346	0.20589
WOODRD	137.5604	137.9311	176.7625	102.6189	18.51582	0.134601
PAPER 3400	6524.815	6563.401	9651.65	3788.462	1411.265	0.216292
PAPERRD	533.9721	480.8158	892.3164	337.1384	164.8355	0.308697
CHEM 3510+3520-3522	6265.069	6460	8754.135	4205.541	1364.835	0.217848
CHEMRD	3633.605	3593.896	5610.842	2464.238	932.0919	0.25652
DRUGS 3522	814.2413	730.6716	1672.865	295.4305	370.6902	0.455258
DRUGSRD	2732.759	2451.017	5556.173	1213.003	1373.863	0.502738
PETRO 3530+3540	2301.858	2201.115	3768.735	1094.831	742.4605	0.322548
PETRORD	1443.655	1448.656	1899.793	865.4376	305.3801	0.211533
RUBBER 3550+3560	1987.455	1948.886	2728.809	1228.251	438.4426	0.220605
RUBBERRD	669.1212	656	916.196	454.669	107.4457	0.160577
NMET 3600	1805.036	1708.958	2534.748	1219.839	382.5129	0.211914
NMETRD	452.7274	406	745.2975	325.5681	130.2932	0.287796
IRON 3710	2551.359	2311.309	3665.714	1233.008	839.0238	0.328854
IRONRD	305.6026	288.7867	536.1821	142.06	127.8518	0.41836
NONFER 3720	1093.476	1096.475	1374.073	816.7785	168.3266	0.153937
NONFERRD	303.3519	304.8397	376.5852	201.6722	43.1897	0.142375
METAL 3810	2172.717	2097.687	2655.927	1752.326	266.8368	0.122812
METALRD	586.7074	586.5005	843.1145	459.1241	93.97976	0.160182
OFFICE 3825	1276.663	1278.166	2285.51	399.7001	534.0123	0.418288
OFFICERD	5435.072	5581.973	8154.875	3011.654	1908.903	0.351219
ELECT 3830-3832	1367.793	1384.392	1623.066	1103.193	138.1217	0.100981
ELECTRD	1972.35	2368.169	3266.001	602.5717	1124.338	0.57005
RADIO 3832	3148.459	3356.743	5273.438	1277.381	1137.881	0.361409
RADIORD	7254.025	7103.3	10942.77	4331.483	2177.408	0.300165
MOTOR 3843	4174.089	4351.396	7691.121	1850.789	1274.947	0.305443
MOTORRD	5417.564	4955	7728.546	3396.672	1400.409	0.258494
PROFG 3850	1508.629	1431.361	2369.035	764.6437	567.3095	0.376043
PROFGRD	3511.639	3588.849	6249.252	1670.051	1374.215	0.391332
OTHER 3900	396.3003	387.5582	519.5179	290.3138	55.4266	0.13986
OTHERRD	318.0727	296.6721	455.5298	274.5766	54.56425	0.171546

The first row for each sector refers to investment, the second row to R&D. Isic classification code are indicated, according to the OECD ANBERD adjustment.
Millions of 1980 dollars.

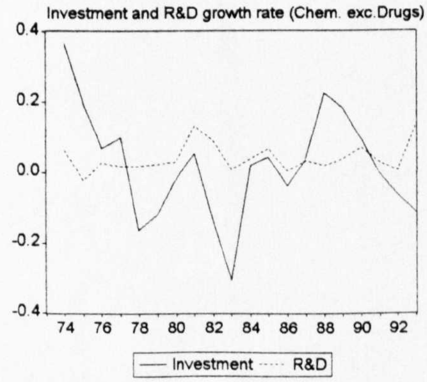
Table A4 Sector Classification ISIC Groups

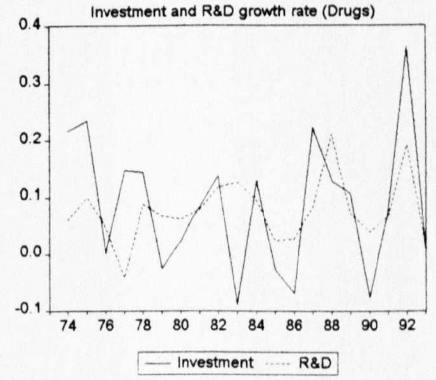
Food, beverages and tobacco	3100
Textiles, apparel and leather	3200
Wood products and furniture	3300
Paper, paper products and printing	3400
Chemical (excl. drugs)	3510+3520-3522
Drugs and medicines	3522
Petroleum refineries and products	3530+3540
Rubber and plastic products	3550+3560
Non-metallic mineral products	3600
Iron and steel	3710
Non-ferrous metals	3720
Metal products	3810
Office and computing equipment	3825
Electrical machines excl. comm.equip	3830-3832
Radio, TV and communication equipment	3832
Motor vehicles	3843
Professional goods	3850
Other manufacturing	3900
Total manufacturing	3000

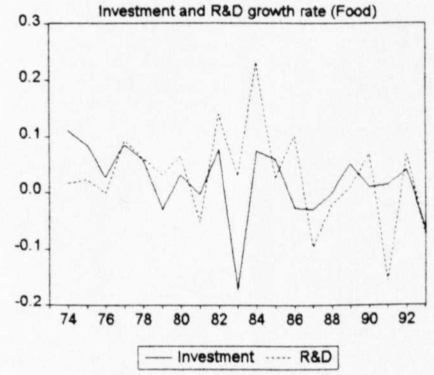
Sources: Investment in machinery and equipment, **OECD, Industrial Structure Statistics,(Annual Data 19773-1993).**
R&D expenditure: **OECD, ANBERD data base, annual data 1973-1993.**

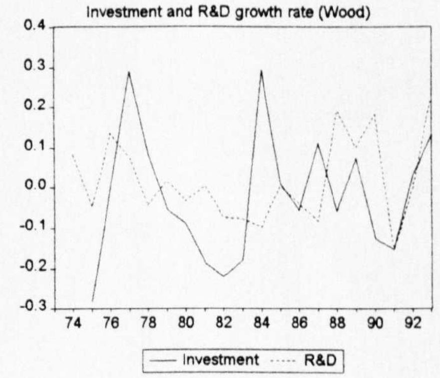
Appendix III

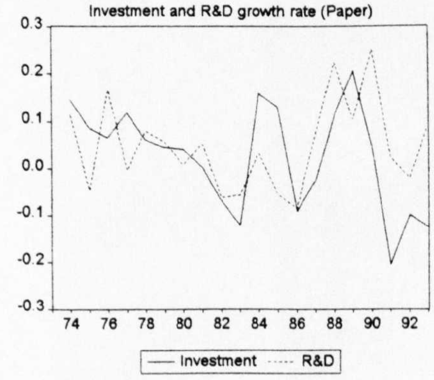
Investment and R&D Growth rate

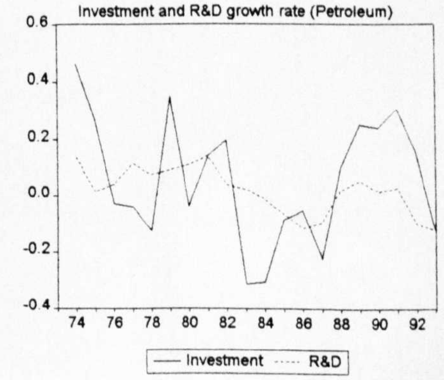


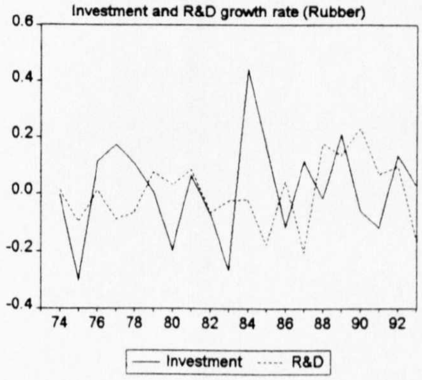


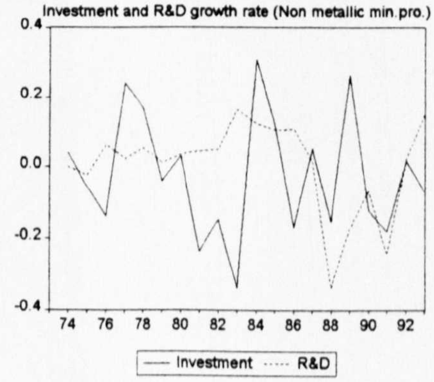


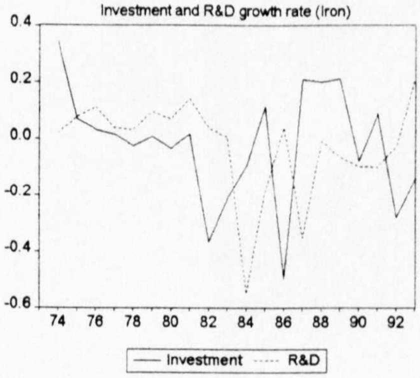


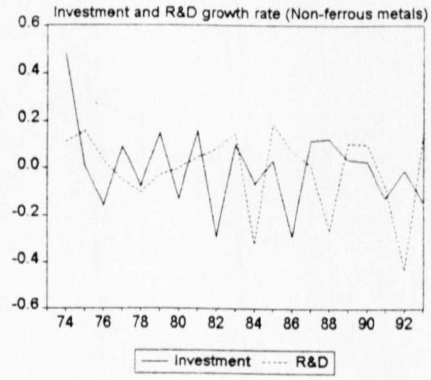


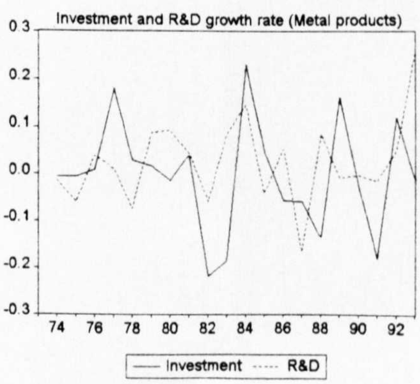


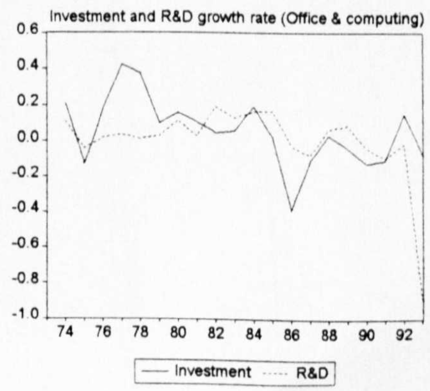

Investment and R&D growth rate (Rubber)
Investment
R&D

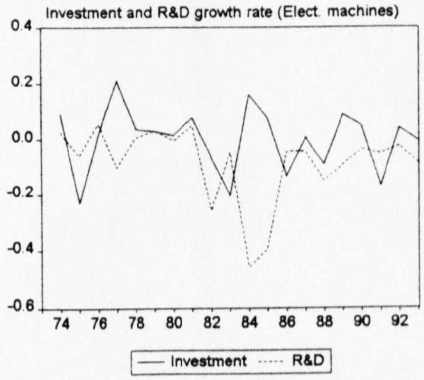

Investment and R&D growth rate (Non metallic min.pro.)
Investment
R&D

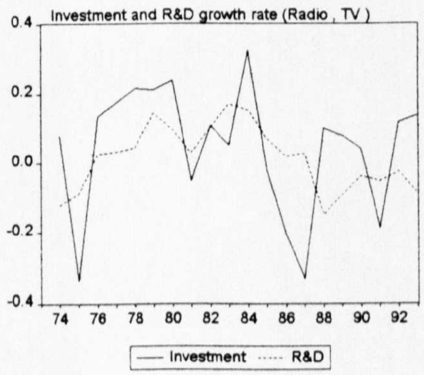

Investment and R&D growth rate (Iron)
Investment
R&D

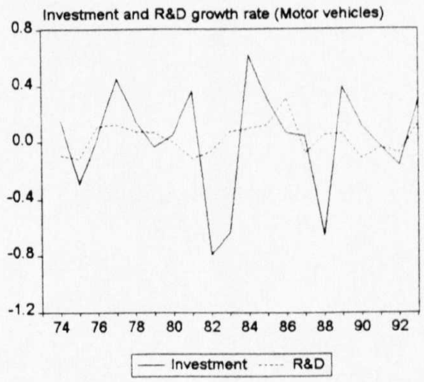

Investment and R&D growth rate (Non-ferrous metals)
Investment
R&D

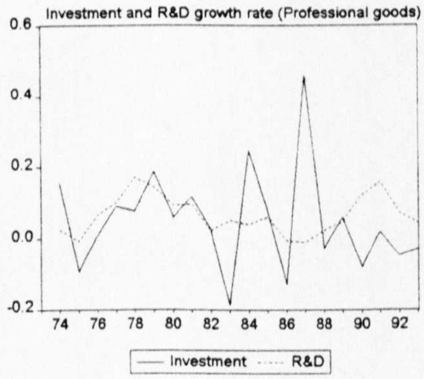

Investment and R&D growth rate (Metal products)
Investment
R&D

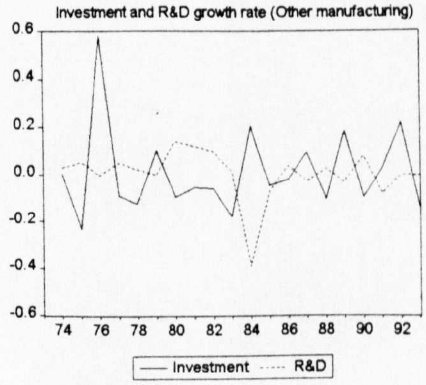

Investment and R&D growth rate (Office & computing)
Investment
R&D

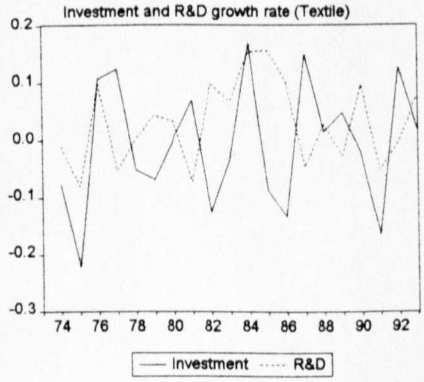

Investment and R&D growth rate (Elect. machines)
Investment
R&D


Investment and R&D growth rate (Radio , TV)
Investment
R&D


Investment and R&D growth rate (Motor vehicles)
Investment
R&D


Investment and R&D growth rate (Professional goods)
Investment
R&D


Investment and R&D growth rate (Other manufacturing)
Investment
R&D


Investment and R&D growth rate (Textile)
Investment
R&D

CHAPTER VII

7. The Interaction between Investment and Output Growth

7.1 Introduction

In the previous chapter we looked at the causal link from R&D to investment. In this chapter we focus on another crucial relationship which needs to be explored, i.e., the link between investment and output growth.

The role of investment within the growth process may be implicitly derived from the endogenous growth models described in the second and fourth chapters. In these models, the intermediate sector sells new capital goods to the final output sector which can therefore increase production by increasing the demand for capital goods. In addition, many empirical studies (De Long and Summer (1991), (1992)) emphasise the effect of investment on output growth, concluding that investment in machinery and equipment may be regarded as the engine of long-run growth. However, the results of these tests are crucially affected by the characteristics of the data set. Typically these tests are built using the Penn World Table data base, which includes data for more than

100 countries. In addition, these tests are based on average values of the variables over long time periods to proxy for long-run values. In this framework causality tests are probably misleading as they include cross country effects which are not adequately taken into account in the proposed test procedures. In a more recent investigation, Blomstrom, Lipsey and Zejan (1996) show that the reverse relationship hold, as contrary to De Long and Summer 's prediction. However, this investigation still has the same drawbacks.

Here, we perform causality tests using a time-series approach which enable us to take into account both short-run and long-run interactions between investment and output, as in our study of the relationship between R&D and investment. In addition, we consider Granger causality in a three-variable framework in which the dynamic interaction between investment, R&D and output is analysed, thus giving an even better indication of pattern of causality.

This analysis, together with the investigation of the causal link between R&D and investment, gives a more realistic and precise picture of the relationship between such crucial variables, and represents a test of the implied assumptions of the theoretical models previously analysed.

7.2 Traditional Granger Causality Tests

In this section we propose the traditional approach to causality tests, as derived from the standard Granger causality tests and from the Hsiao version. The arguments discussed in section 5.3 also apply for this investigation.

Therefore we first analyse the time series properties of each variable and then perform causality tests. The data being used refer to real investment in machinery and equipment and real GDP over the US economy for the period 1953-1993, with summary statistics and sources given in the Appendix of this chapter.

Table 7.1 shows the results of unit root tests for the investment and output variables.

Table 7.1 *ADF* **tests***

	lmaceqr	*lgdp*
k(1)	-10.1967	-7.719
t(1)	-2.2120	-1.976
F(0,0,1)	4.73	9.84
F(0,1)	2.92	2.72

lmacqrr= natural log of real investment in machinery and equipment
lgdp= natural log of real GDP
*The test involves the estimation of the following equation:

$$z_t = \alpha + \rho z_{t-1} + \beta t + \sum_{i=1}^{k} \phi_i \Delta z_{t-i} + \varepsilon_t$$

k, the number of lags on the differentiated term, is set equal to one, sufficient to get a white noise error term
Critical values (0.05 significance level) are as follows: k-test-22.5, t-test -4.38, F(0,0,1) test 5.68, F(0,1) test 10.61

As in the analysis made in section 6.3, the results of table 7.1 suggest that the unit root hypothesis cannot be rejected. In addition, a unit root test on the differentiated series suggests that both series are integrated of order one with the inclusion of a drift term.[1] We therefore specify the causality tests in a differentiated vector autoregression. It is worth noting that in this case the test involves causality between the growth rate of investment and the growth rate of output, as we consider log differences of both variables.

We again apply the *Final Prediction Error* criteria *(FPE)*, the *AIC* criteria and the likelihood ratio test *(LR)* to select the optimal lag length in a bivariate *VAR*, with the results given in Table 7.2.

Table 7.2 Optimal lag selection*

Lags	*Δlmaceqr* AIC	FPE	*Δlgdp* AIC	FPE	LR♣
3	-66.4577	$4.41x(10)^{-3}$	-122.71	$5.9x(10)^{-4}$	χ^2 =6.680
2	-65.6322	$4.49x(10)^{-3}$	-139.84	$5.7x(10)^{-4}$	

* We do nor show the value of the statistics for other lag length as they are above the values of the two and three lag selections.
♣The statistic is $(T-c)\left(\ln|\Sigma_r|-\ln|\Sigma_u|\right)$ where Σ_r and Σ_u are the restricted and unrestricted covariance matrices, T is the number of observations and c is a correction to improve small sample properties (see Sims (1980)).

Table 7.2 clearly shows that the two-lag specification is preferred in the equation of *Δlgdp*, while in the *Δlmaceqr* equation the *AIC* and *FPE* values are close for the three- and two-lag specification. The *LR* test suggests, on the

[1] Given that the hypothesis of a unit root was not rejected, we also tested for the significance of the trend and drift terms.

Significance of the trend and drift terms*

	lmaceqr	*lgdp*
trend	-0.606	-0.685
drift	3.164	7.543

* Trend refers to the t-statistic of the coefficient on the TREND variable in the regression of Δz_t on a constant and a linear trend. Drift refers to the t statistic of the coefficient on the constant term in the regression of Δz_t on a constant. The error terms of these equations are again tested for autocorrelation, providing evidence that the hypothesis of white noise error cannot be rejected.

other hand, a two-lag specification. Nevertheless, we perform the test using both the two-and three-lag specification and compare the results.

Table 7.3 shows F tests concerning the regressions of $\Delta lmaceqr$ and $\Delta lgdp$ on their own lagged values and lagged values of the other variable.

Table 7.3 Causality tests

Three-lag specification		*Two-lag specification*	
Output→Investment	*Investment→Output*	*Output→Investment*	*Investment→Output*
$F_{3,29}$=2.092	$F_{3,29}$=2.370	$F_{2,31}$=2.688	$F_{2,31}$=2.899
Critical value = 2.94 (0.05 significance level)			

The sample period for the test is 1958-1993, corresponding to the sample size used for the lag selection tests.

The tests suggest that investment and output show bidirectional causality as each variables enters the equation of the other with significant lagged values. This is more evident in the two lag specification where the F test is very close to the 0.05 significance level in both equations.

We also perform the Hsiao version of Granger causality which implies the calculation of the *FPE* of the autoregressive process associated with each variable.

Table 7.4 *FPE* of a one dimensional autoregressive process of the R&D and Investment variables.

Lags	$\Delta lmaceqr$ $(x10)^{-3}$	$\Delta lgdp$ $(x10)^{-4}$
2	5.56	6.1
3	5.81	6.3
4	6.15	6.7

The results in Table 7.4 show that the optimal lag length is two for both series as the *FPE* is minimised. However, each variable enters the equation as an explanatory variable with just one lag as shown in Table 7.5.

Table 7.5 Hsiao causality tests

$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{1i} \Delta lmaceqr_{t-i} + \beta \Delta \lg dp_{t-i} + \varepsilon_{1t}$
FPE=5.05x(10)$^{-3}$
$\Delta \lg dp = \sum_{i=1}^{2} \gamma_{1i} \Delta \lg dp + \delta \ \Delta lmaceqr + \varepsilon_{2t}$
FPE=5.5x(10)$^{-4}$
$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{2i} \Delta lmaceqr + \varepsilon_{3t}$
FPE=5.56x(10)$^{-3}$
$\Delta \lg dp = \sum_{i=1}^{2} \gamma_{2i} \Delta \lg dp + \varepsilon_{4t}$
FPE=6.1x(10)$^{-4}$

The results confirm a bidirectional causality between the two variables as the *FPE* error in both equations is reduced when we introduce lagged values of the other variable.

7.3 Long-Run Relationship

We have also used the Granger representation theorem to test for causality in both the short-run and the long-run using a vector error correction specification. One can use this specification if output and investment are cointegrated, i.e., there is a linear combination of the two series which is stationary. We consider again the system

$$(7.1)\quad \Delta z_t = \sum_{i=1}^{k} \delta_{1i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{2i} \Delta x_{t-i} + \delta_3 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{1t}$$

$$(7.2)\quad \Delta x_t = \sum_{i=1}^{k} \delta_{5i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{6i} \Delta z_{t-i} + \delta_7 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{2t}$$

and test for cointegration using the Johansen procedure.

Table 7.5 Johansen cointegration tests

	Null hypothesis (1)	*Null hypothesis (2)*
Lags	$r \leq 1$	$r=0$
2	2.42	6.7
3	3.23	13.59

The test includes a constant term in the VEC specification.
The sample size is 1958-1993 as for causality tests. r= number of cointegrating vectors
The 0.05 critical values are 3.76 and 15.41 respectively for hypothesis (1) and hypothesis (2).

In this case the vector error correction *(VEC)* specification and the implied tests for cointegration do not show clear results. In the two-lag specification investment and output do not appear to be cointegrated. The null hypothesis (2) of no cointegrating vectors cannot be rejected. In the three-lag specification this hypothesis is rejected, while the null hypothesis (1) of one cointegrating vector is not rejected, however, with a value near to the 0.05 critical value.[2]

Keeping these results in mind, we used the three lag *VEC* specification to test for causality between investment and output.

Table 7.6 Granger causality in the augmented *VAR* representation *(k=3)*

	Output→Investment	
$\delta_3=0$	$\delta_{2i}=0$	$\delta_{2i}=0$, $\delta_3=0$
$F_1=9.24$	$F_2=3.218$	$F_3=4.326$
	Investment→Output	
$\delta_7=0$	$\delta_{6i}=0$	$\delta_7=0$, $\delta_{6i}=0$
$F_4=3.83$	$F_5=2.93$	$F_6=2.91$

The results of this test procedure show that although the coefficients of lagged values of output growth rate are more significant than the corresponding values of lagged investment, the direction of causality is bidirectional. In other words, there is both a short-run and a long-run feed-back between the two variables.

This finding is important as it sheds light on a crucial economic relationship which has been emphasised in the empirical literature. As we have emphasised before, on the one hand De Long and Summers underline that machinery equipment investment is strongly correlated to output growth thus assuming a key role in the growth process of the economy. On the other hand, in their panel investigation Blomstrom, Lipsey and

[2] We have also tested for cointegration using the Engle and Granger methodology and the results confirm the Johansen procedure, i.e., the two variables may be cointegrated at the 0.10 significance level.

Zejan (1996), find that output growth causes investment and not the reverse, thus concluding that De Long and Summers' arguments in favour of policies encouraging capital formation are overestimated.

Our investigation, which is a pure time-series analysis and thus strictly applies the concept of causality, shows both short-run and long-run feed-backs between investment and growth, giving a more realistic picture of the relationship between these variables. It has to be emphasised that the previous investigations dealt with average (five year averages) data on a panel of more than 100 countries and therefore they cannot properly take into account the dynamic interaction between investment and growth (which is also affected by country specific effects not adequately accounted for by fixed effects models). This highlights the relevance of our findings, which may be used for investigation in other economic frameworks.

7.4 The Dynamic Response of Output Growth

The underlying vector autoregression in table 7.3 (in the two-lag specification) may also be used to verify the dynamic response of output growth rate to a random shock in investment growth rate. This allows us to compare our results to previous empirical findings.

Before analysing this dynamic effect, it is worth recalling the main theoretical assumptions underlying the impulse response analysis. Consider for simplicity a *VAR* model with only one lag in each variable:

$$(7.3)\quad x_t = \alpha_{11}x_{t-1} + \alpha_{12}z_{t-1} + \mu_{1t}$$

$$(7.4)\quad z_t = \alpha_{21}x_{t-1} + \alpha_{22}z_{t-1} + \mu_{2t}$$

The system (5.22- 5.23) may be written in terms of the lag operator L as

$$(7.5)\quad \begin{bmatrix} 1-\alpha_{11}L & -\alpha_{12}L \\ -\alpha_{21}L & 1-\alpha_{22}L \end{bmatrix}\begin{bmatrix} x_t \\ z_t \end{bmatrix} = \begin{bmatrix} \mu_{1t} \\ \mu_{2t} \end{bmatrix}$$

The solution of the system is

$$(7.6)\quad \begin{bmatrix} x_t \\ z_t \end{bmatrix} = \begin{bmatrix} 1-\alpha_{11}L & -\alpha_{12}L \\ -\alpha_{21}L & 1-\alpha_{22}L \end{bmatrix}^{-1}\begin{bmatrix} \mu_{1t} \\ \mu_{2t} \end{bmatrix}$$

and

$$(7.7)\quad \begin{bmatrix} x_t \\ z_t \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} 1-\alpha_{11}L & -\alpha_{12}L \\ -\alpha_{21}L & 1-\alpha_{22}L \end{bmatrix}\begin{bmatrix} \mu_{1t} \\ \mu_{2t} \end{bmatrix}$$

where Δ is the determinant of the *RHS* matrix in system (7.5). The autoregression version of system (7.5) may be expressed in its moving average representation, i.e., one can express x_t and z_t as functions of the current and lagged values of μ_{1t} and μ_{2t} (system (7.7)). This solution may be used to calculate the so-called impulse response functions, which show the current and lagged effects over time of changes in μ_{1t} and μ_{2t}.

However, this methodology has the drawback that in order to identify the original *VAR* system one must impose some identifying restrictions. One commonly used restriction is represented by the Cholesky decomposition of innovations μ_1 and μ_2. This methodology constrains some innovation shocks to have no simultaneous effect on one variable, thus imposing an implicit causal ordering.[3]

For the purposes of our investigation we use the Cholesky decomposition to verify the dynamic response of output growth to an investment shock, thus comparing our results with the results expected from endogenous growth models. In this case we hypothesises that an output shock at time t has no simultaneous effects on investment, while an investment shock does affect output simultaneously. This specification allows us to verify the possible long-run effect of a shock running from investment to output , showing whether it is consistent with the predictions of previous theoretical and empirical investigations. It is worth noting that in both the unconditional *VAR* and in the *VEC* specification, where the long-run adjustment is taken into account, the effect of an investment shock approaches zero between 6 to 8 years, which is about half that predicted in De Long and Summers' conclusions.

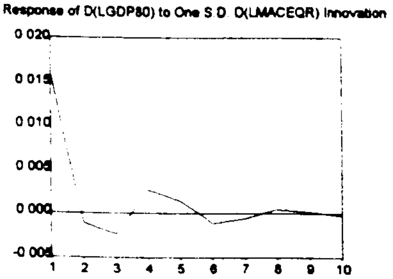


Figure 7.1 *Dynamic response of output in the unconditional VAR (2 lags)*

[3] Other identification methodology derives from structural *VAR*, such as that proposed in Bernanke and Sims (1986) and Blanchard and Quah (1989).

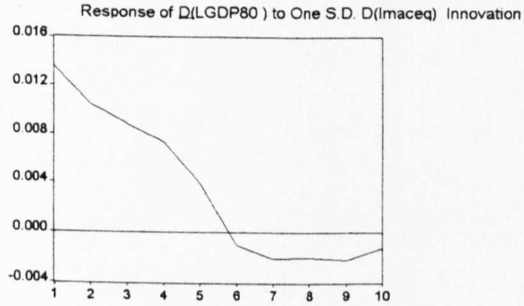


Figure 7.2 *Dynamic response of output growth in the VEC specification*

The results of our dynamic responses are therefore consistent with other results (Jones 1995) which show that investment has a short-to medium-term effect on the growth rate, but thereby ruling out the long term effect (15 years on average) hypothesised by De Long and Summer.

7.5 Conditional Granger Causality (R&D, Investment, Output Growth)

In the previous sections we analysed Granger causality in a two-variable case, ignoring possible feed-back derived from other sources. In this section we consider Granger causality in a three-variable framework, i.e., we take investment, R&D and output into account simultaneously. Granger causality is in this case conditional upon the inclusion of all the variables in the system. We first consider a simple trivariate *VAR* and then the *VEC* specification implied by the Granger representation theorem of cointegrated variables.

Table 7.7 Conditional Granger Causality tests in a two and three lag *VAR* specification

R&D→Investment	*Output→Investment*	*Investment→R&D*	*Output→R&D*
$F_{3,31}$= 4.934	$F_{3,31}$= 1.98	$F_{2,31}$= 2.40	$F_{2,31}$= 4.66

Investment→Output	***R&D→Output***
$F_{2,31}$= 2.703	$F_{2,31}$= 2.156

Critical value = 2.94 (0.05 significance level)

Table 7.7 clearly shows that R&D also Granger causes investment in this augmented version. This result reinforces the previous causality test based on a bivariate autoregression between investment and R&D. The value of the *F* test is far above the 0.05 critical value implying that this finding is robust to different specifications. The reverse causal link is significant for significance levels higher than the 0.05 level.

Output also causes R&D, with an F test much higher than the 0.05 significance level. The reverse link holds only for a higher significance level. In this trivariate system the relationship between investment and output is less significant than in the previous bivariate version. In general, the most robust relationship emerges between R&D and investment, on the one hand, and output and R&D on the other. The first causal link has been analysed in depth in the previous sections and this trivariate version further reinforces that evidence.

Causality from output to R&D is more significant than in the reverse direction, i.e., from R&D towards output and may be rationalised by noting that as output growth increases, more resources are available to further investment opportunities, including R&D. The reverse relationship is not direct, as we have described above. R&D may affect first investment, and then through this route, output growth.

We also perform a causality test using a trivariate vector error correction representation as is shown in equations (7.8- 7.10).

$$(7.8)\quad \Delta z_t = \sum_{i=1}^{k} \delta_{1i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{2i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{3i} \Delta y_{t-i} + \delta_4 (z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{1t}$$

$$(7.9)\quad \Delta x_t = \sum_{i=1}^{k} \delta_{7i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{8i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{9i} \Delta y_{t-i} + \delta_{10} (z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{2t}$$

$$(7.10)\quad \Delta y_t = \sum_{i=1}^{k} \delta_{11i} \Delta y_{t-i} + \sum_{i=1}^{k} \delta_{12i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{13i} \Delta y_{t-i} + \delta_{14} (z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{3t}$$

Tables 7.8 and 7.9 show the results of cointegration tests in a two-and three-lag specification.

The first table shows tests based on the assumption of no deterministic trend in the data, while the second test allows for the inclusion of a linear deterministic trend. In both cases we reject the hypothesis of no cointegration and cannot reject the hypothesis of the existence of one or two cointegrating vectors.

Table 7.10 and 7.11 report the results of the causality tests. The relationships between investment and R&D and output and R&D are the most significant and robust to different specifications. In the two-lag specification (with no deterministic trend) R&D causes investment. The inverse causal link holds for a higher significance level. Output causes investment, while investment causes output for a significance level higher than 0.10 .

R&D and output clearly show bidirectional causality with *F* values which are above the 0.05 significance level. It is worth noting, however, that the cointegrating vector is significant only in the output equation in both the two-and three-lag specification.

This means that the adjustment to long-run disequilibrium is driven by the output variable. Both investment and R&D do not respond to discrepancy from long-run equilibrium in this trivariate *VEC* specification. In other words, there is long-run causality running from both R&D and investment towards output. This suggests that the possible long-run effect of investment on output growth must be considered conditional on the inclusion of other variables (e.g. R&D) in any dynamic model. As we have seen before, investment alone explains little regarding the long-run fluctuations in output growth.

The same argument applies to the impact of R&D on output growth. In this trivariate case the long-run effect of this variable is significant, as it is combined with the effect of investment.

Table 7.8 Johansen cointegration tests

	Null hypothesis (1)	Null hypothesis (2)	Null hypothesis (3)
Lags	$r \leq 2$	$r \leq 1$	$r=0$
2	5.23	13.32	41.18
	0.05 c.v. 9.24	0.05 c.v. 19.96	0.05 c.v. 34.91

The test is based on the assumption of no deterministic trend in the data.
The sample size is 1958-1993 as for the causality tests. r= number of cointegrating vectors.

Table 7.9 Johansen cointegration tests

	Null hypothesis (1)	Null hypothesis (2)	Null hypothesis (3)
Lags	$r \leq 2$	$r \leq 1$	$r=0$
3	1.72	10.93	45.17
	0.05 c.v. 3.76	0.05 c.v. 15.41	0.05 c.v. 29.68

The test is based on the assumption of a linear deterministic trend in the data.
The sample size is 1958-1993 as for the causality tests. r= number of cointegrating vectors

Table 7.10 Conditional Granger causality in the augmented *VAR* representation *(k=2)*

	Output→Investment	
$\delta_4=0$	$\delta_{3i}=0$	$\delta_4=0, \delta_{3i}=0$
$F_1=1.796$	$F_2=3.240$	$F_3=5.021$
	R&D→Investment	
$\delta_4=0$	$\delta_{2i}=0$	$\delta_4=0, \delta_{2i}=0$
$F_4=1.796$	$F_5=3.404$	$F_6=2.572$

	Output→R&D	
$\delta_{10}=0$	$\delta_{9i}=0$	$\delta_{10}=0, \delta_{9i}=0$
$F_1=1.726$	$F_2=4.825$	$F_3=4.923$
	Investment→R&D	
$\delta_{10}=0$	$\delta_{8i}=0$	$\delta_{10}=0, \delta_{8i}=0$
$F_4=1.726$	$F_5=2.48$	$F_6=2.792$

	Investment→Output	
$\delta_{14}=0$	$\delta_{12i}=0$	$\delta_{14}=0,\delta_{12i}=0$
$F_1=18.778$	$F_2=2.195$	$F_3=13.656$
	R&D→Output	
$\delta_{14}=0$	$\delta_{13i}=0$	$\delta_{14}=0,\delta_{13i}=0$
$F_4=18.778$	$F_5=3.479$	$F_6=6.289$

Table 7.11 Conditional Granger causality in the augmented *VAR* representation *(k=3)*

	Output→Investment	
$\delta_4=0$	$\delta_{3i}=0$	$\delta_4=0, \delta_{3i}=0$
$F_1=0.792$	$F_2= 1.078$	$F_3=0.975$
	R&D→Investment	
$\delta_4=0$	$\delta_{2i}=0$	$\delta_4=0, \delta_{2i}=0$
$F_4=0.792$	$F_5=2.825$	$F_6=3.037$

	Output→R&D	
$\delta_{10}=0$	$\delta_{9i}=0$	$\delta_{10}=0$, $\delta_{9i}=0$
$F_1=0.567$	$F_2=2.515$	$F_3=2.218$
	Investment→R&D	
$\delta_{10}=0$	$\delta_{8i}=0$	$\delta_{10}=0$, $\delta_{8i}=0$
$F_4=0.567$	$F_5=2.614$	$F_6=1.986$

	Investment→Output	
$\delta_{14}=0$	$\delta_{12i}=0$	$\delta_{14}=0,\delta_{12i}=0$
$F_1=4.441$	$F_2=1.761$	$F_3=2.169$
	R&D→Output	
$\delta_{14}=0$	$\delta_{13i}=0$	$\delta_{14}=0,\delta_{13i}=0$
$F_4=4.441$	$F_5=3.554$	$F_6=2.703$

7. 6 Conclusions

In this chapter we have considered the possible causal link between investment and output growth. Although endogenous growth models attach a key role to investment in explaining long-run differences in the growth rate between world economies, empirical findings are still controversial. Causality tests suggest that bidirectional causality emerges between these variables in a pure time-series framework. In addition , we have considered impulse response functions in order to verify the impact of an investment shock on the output growth rate. The impact is significant and declining over time, showing that investment may affect the output growth rate but mainly in the short to medium term.

We have also considered the dynamics of R&D, investment and output simultaneously. This allows us to specify a trivariate *VAR* model where causality is tested as being conditional upon the inclusion of a third variable. Causality running from R&D to investment is reinforced, suggesting that this finding is robust to different specifications. Bidirectional causality also emerges for the other variables. However, the most significant relationship is that running from output to R&D.

In the vector error correction representation of this trivariate model, it is worth underlining that any long-run adjustment to disequilibrium is determined by the adjustment coefficient in the output equation. In the other equations this coefficient is not significant. This finding suggests that R&D and investment may have a long-run effect on output growth rate if they are considered simultaneously.

Our empirical investigation supports the theoretical models analysed in the previous sections, in that R&D does cause investment. On the other hand, the role of investment in the growth process is probably overestimated by the endogenous growth model as we do not find causality running from investment to output growth. Bidirectional causality is the link that emerges between these variables. In addition, the effect of an investment shock on the output growth rate is confined to the short-medium term and not to the long-run as implicitly assumed in previous theoretical models and empirical investigations.

Appendix

Table A1 Data Sources

GDP= Gross Domestic Product.

Source: OECD, National Accounts (Annual Data 1953-1993)

MACEQ= Machinery and Equipment Investment.

Source: OECD, National Accounts (Annual Data 1953-1993)

The GDP deflator is calculated from the GDP statistics of **the OECD National Accounts, (Annual Data, 1953-1993)**.

LGDP= natural log of real GDP

LMACEQR= natural log of real investment in machinery and equipment (deflated by 1980 GDP deflator)

Table A2 Sample Statistics (Mean, Standard Deviation)

Variable	***Mean***	***SD***
lmaceqr	11.667	0.514
lgdp	14.666	0.326

CHAPTER VIII

8. R&D, Investment and Growth: the UK Evidence

8.1 Introduction

In this chapter we analyse the interaction between R&D, investment and growth in the UK economy, following the methodological approach analysed in Chapter 6. This investigation is important as it allows us to compare the results of the causality tests within different economic frameworks, thus giving us the opportunity to verify if such relationships may be considered as stylised facts. We are particularly interested in testing the causal link between R&D and investment and investment and growth, according to the theoretical discussions described in the previous chapters. We have found that in the US economy the causal link between R&D and investment runs from the former to the latter in the short-run, while there is evidence of a long-run feed-back. In addition, bi-directional causality emerges between investment and output, suggesting that the impact of investment on growth is overestimated in the endogenous growth literature. The analysis for the UK economy allows us to further test these crucial links and thus verify the pattern of these variables in two different economic frameworks.

8.2 Causality Between R&D and Investment

In this section we show the results of traditional Granger causality in the UK economy and compare them with those derived for the US economy. We first consider the relationship between R&D and investment and the time-series properties of these variables. The time series used in this analysis refer to Gross Domestic Expenditure in R&D (GERD) and annual aggregate investment in machinery and equipment over the period 1955-1991. Both series are deflated using the GDP deflator and summary statistics and sources are reported in the Appendix.

8.2.1 Unit Root Tests and Traditional Granger Causality Tests

Table 8.1 *ADF* **tests***

	lmaceqr	*lrrduk*
k(1)	-19.240	-14.783
t(1)	-4.067	-3.150
F(0,0,1)	6.317	4.631
F(0,1)	8.731	5.228

lmacqrr= natural log of real investment in machinery and equipment
lrrduk= natural log of real R&D expenditure
*The test involves the estimation of the following equation:

$$z_t = \alpha + \rho z_{t-1} + \beta t + \sum_{i=1}^{k} \phi_i \Delta z_{t-i} + \varepsilon_t$$

k, the number of lags on the differentiated term, is set equal to one, sufficient to obtain a white noise error term (ε_t).
Critical values (0.05 significance level) are as follows: k-test-22.5, t-test -4.38, F(0,0,1) test 5.68, F(0,1) test 10.61.

From table 8.1 the unit root hypothesis cannot be rejected and the *F(0,01)* and *F(0,1)* test suggest the inclusion of a drift term in the data generating mechanism.

Table 8.2 enables us to select the optimal lag length according to the *AIC*, *FPE* and *LR* criteria.

Table 8.2 Optimal lag selection*

Lags	*Δlmaceqr*		*Δlrrduk*		
	AIC	FPE	AIC	FPE	LR⁺
3	-63.02	$4.50x(10)^{-3}$	-50.08	$6.69x(10)^{-4}$	$\chi^2(4)$=6.87 0.05 c.v. 9.49
2	-68.53	$3.93x(10)^{-3}$	-55.41	$5.78x(10)^{-3}$	
1	-68.03	$4.09x(10)^{-3}$	-59.86	$5.17x(10)^{-3}$	

* We do not show the value of the statistics for other lag lengths as they are above the values of the two- and three-lag selections.

⁺The statistic is $(T-c)(\ln|\Sigma_r|-\ln|\Sigma_u|)$ where Σ_r and Σ_u are the restricted and unrestricted covariance matrices, T is the number of observations and c is a correction to improve small sample properties (see Sims (1980)). The test refers to the choice between two-and one-lag length.

The *AIC* and *FPE* criteria show that the two-lag specification is preferred for the investment variable while just one lag is needed for the R&D variable to satisfy both criteria. The *LR* suggests that one lag is preferred and thus we decided to perform the Granger causality tests with both one-and two-lag specifications.

Table 8.3 shows traditional causality tests with different lag specifications suggesting that, contrary to the US evidence, R&D does not cause investment. However, nor does the inverse relationship, i.e., causality running from investment to R&D, find support in the UK data.

Table 8.3 Causality tests

One lag specification		***Two lag specification***	
R&D→Investment	*Investment→R&D*	*R&D→Investment*	*Investment→R&D*
$F_{1,32}$=0.5	$F_{1,32}$=0.306	$F_{3,27}$=0.183	$F_{3,27}$=0.284

Critical value = 2.94 (0.05 significance level)

The sample period for the test is 1955-1991.

This evidence is confirmed by the Hsiao version of Granger causality, in that the *FPE* error of the regression of lagged values of the controlled variable does not improve with the inclusion of lagged values of the manipulated variable.[1]

Table 8.4 *FPE* of a one dimensional autoregressive process of the R&D and Investment variables.

Lags	$\Delta lmaceqr$	$\Delta lrrduk$
	$(x10)^{-3}$	$(x10)^{-3}$
1	3.93	4.93
2	3.52	5.29
3	3.83	5.70

Table 8.5 Hsiao causality tests

$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{1i} \Delta lmaceqr_{t-i} + \beta lrrduk_{t-i} + \varepsilon_{1t}$
FPE=3.70x$(10)^{-3}$
$\Delta lrrdusa = \gamma_{1j} \Delta lrrdusa + \delta \ \Delta lmaceqr + \varepsilon_{2t}$
FPE=5.17x$(10)^{-3}$
$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{2i} \Delta lmaceqr_{t-j} + \varepsilon_{3t}$
FPE=3.52x$(10)^{-3}$
$\Delta lrrdusa = \gamma_2 \Delta lrrdusa + \varepsilon_{4t}$
FPE=4.93x$(10)^{-3}$

As shown in table 8.6, the optimal lag for the investment variable is two, while for R&D it is one, while both variables enter the test equation with just one lag.

[1] See section 5.3 for a description of the methodology.

8.3 Long-Run Relationship

The long-run properties of the variables are again analysed through cointegration techniques, as in the analysis given in chapter 5. In this case the Johansen cointegration tests do not show clear results, as the variables do not appear to be cointegrated at the 0.05 significance level using different lag specifications.

Table 8.6 Johansen cointegration tests

	Null hypothesis (1)	*Null hypothesis (2)*
Lags	$r \leq 1$	$r=0$
1	5.33	14.72
2	5.28	11.61
3	4.53	10.30

The test is based on the hypothesis of no deterministic trend in the data.
The sample size is 1955-1991 as for the causality tests. r= number of cointegrating vectors
The 0.05 critical values are 9.24 and 19.96 respectively for hypothesis (1) and hypothesis (2).

The null hypothesis of zero cointegrated vectors is not rejected at the 0.05 significance level in the specification with one lag, while in the other specifications this hypothesis is not rejected even for lower significance levels. We have also used the Engle and Granger[2] methodology to further test for cointegration, as the results of the Johansen technique may be affected by the small size of the sample. We then estimate a *VEC* model to test the existence of a long-run relationship between the two variables. The Engle and Granger methodology may be simply considered by looking at an error correction model of the form:

[2] See Engle and Granger (1987).

$$(8.1) \qquad \Delta y_t = \gamma \Delta x_t + \alpha(y - \beta x)_{t-1} + \mu_t$$

In this model the change in y is associated with the change in x and with past value disequilibrium, i.e., the cointegrating equation $(y-\beta x)_{t-1}$. Engle and Granger suggest estimating the cointegrating equation first and then the short-run dynamics. This implies estimating the parameter β through a simple OLS regression and , given this first step, estimating the short-run parameters by again using an OLS regression. We have used this procedure after testing the residuals of the regression of y_{t-1} against x_{t-1} for unit root. The test enables us to reject the unit root hypothesis at the 0.10 significance level, thus indicating that the two variables may be cointegrated only at that significance level.[3]

Table 8.7 Granger causality in the augmented *VAR* using the Engle and Granger cointegrating vector

	R&D→Investment	
$\delta_3=0$	$\delta_{2i}=0$	$\delta_{2i}=0, \delta_3=0$
$F_1=1.69$	$F_2=1.35$	$F_3=1.79$
	Investment→R&D	
$\delta_7=0$	$\delta_{6i}=0$	$\delta_7=0, \delta_{6i}=0$
$F_4=4.74$	$F_5=3.2$	$F_6=3.00$

*no constant is included in the VEC specification

The implied VEC is:

$$\Delta z_t = \sum_{i=1}^{k} \delta_{1i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{2i} \Delta x_{t-i} + \delta_3 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{1t}$$

$$\Delta x_t = \sum_{i=1}^{k} \delta_{5i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{6i} \Delta z_{t-i} + \delta_7 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{2t}$$

In this specification, investment causes R&D in the long-run and in the short-run the significance of lagged investment cannot be rejected at the 0.08 significance level. It

[3] The *ADF* test of the residuals of the regression of y_{t-1} against x_{t-1} is -2.938 (without constant term and trend).

is worth noting that this evidence is just the opposite of the US evidence but confirms other UK investigations based on individual (firm) data.[4]

8. 4 The Interaction Between Output and Investment

Table 8.8 shows the results of unit root tests for investment and output variables, suggesting that both series are integrated of order one with the inclusion of a drift term.[5]

Table 8. 8 ***ADF* tests***

	lmaceqr	*lgdp*
k(1)	-19.240	-10.589
t(1)	-4.067	-2.516
F(0,0,1)	6.317	6.718
F(0,1)	8.731	3.374

lmacqrr= natural log of real investment in machinery and equipment
lgdp= natural log of real GDP
*The test involves the estimation of the following equation:

$$z_t = \alpha + \rho z_{t-1} + \beta t + \sum_{i=1}^{k} \phi_i \Delta z_{t-i} + \varepsilon_t$$

k, the number of lags on the differentiated term, is set equal to one, sufficient to get a white noise error term
Critical values (0.05 significance level) are as follows: k-test-22.5, t-test -4.38, F(0,0,1) test 5.68, F(0,1) test 10.61.

We then apply the causality tests to the differentiated series, after choosing the appropriate lag length. It is worth recalling that the test involves causality between the growth rate of investment and the growth rate of output as the two variables are expressed in terms of log-differences.

[4] See Toivanen and Stoneman (1997).
[5] As in the previous sections we have run a unit root test on the differentiated series, which allows us to reject the null hypothesis and thus argue that both series are *I(1)*.

Table 8.9 Optimal lag selection*

Lags	$\Delta lmaceqr$		$\Delta lgdp$		
	AIC	FPE	AIC	FPE	LR♣
3	-70.43	$3.61x(10)^{-3}$	-133.05	$5.41x(10)^{-4}$	$\chi^2(4)$=8.72 0.10 c.v.= 7.78
2	-74.02	$3.34x(10)^{-3}$	-136.85	$5.26x(10)^{-4}$	
1	-71.77	$3.36x(10)^{-3}$	-143.60	$4.74x(10)^{-4}$	

♣ See Table 8.2 for a description of the test.

The tests show that the optimal lag length is two for the investment variable according to both the *AIC* and *FPE* criteria, while for the output variable one time lag is needed to satisfy the information criteria adopted. However, the *LR* test which involves the entire *VAR* system, suggests a two-lag specification. In table 8.10 we show the causality tests using the two-lag specification and also a specification with just one lag and three lags.

Table 8.10 Causality tests

One lag specification		***Two lag specification***	
Output→Investment	*Investment→Output*	*Output→Investment*	*Investment→Output*
$F_{1,34}$=4.21	$F_{1,34}$=0.36	$F_{2,32}$=2.70	$F_{2,32}$=0.30
Critical value = 2.94 (0.05 significance level)			

The sample period for the test is 1955-1991.

The results show that output growth causes investment growth and not the reverse. The *F* tests in the two and three lag specification are significant at the 0.09 level while in the one lag specification the significance level increases to 0.05.

This result is confirmed by the Hsiao version of the Granger causality tests, as output growth reduces the *FPE* error in the investment equation. This evidence again underlines the difference between the UK and US economies, in that the latter shows bi-directional causality while in the former there is a clear short-run causality running from output growth rate to investment growth rate.

Table 8.11 *FPE* of a one-dimensional autoregressive process of the R&D and Investment variables.

Lags	$\Delta lmaceqr$ $(x10)^{-3}$	$\Delta lgdp$ $(x10)^{-4}$
1	3.93	4.51
2	3.52	4.83
3	3.83	5.03

Table 8.12 Hsiao causality tests

$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{1i} \Delta lmaceqr_{t-i} + \beta \Delta \lg dp_{t-i} + \varepsilon_{1t}$
FPE= 3.15 x$(10)^{-3}$
$\Delta \lg dp = \sum_{i=1}^{2} \gamma_{1i} \Delta \lg dp + \delta \ \Delta lmaceqr + \varepsilon_{2t}$
FPE= 4.72x$(10)^{-4}$
$\Delta lmaceqr = \sum_{i=1}^{2} \alpha_{2i} \Delta lmaceqr + \varepsilon_{3t}$
FPE=3.52x$(10)^{-3}$
$\Delta \lg dp = \sum_{i=1}^{2} \gamma_{2i} \Delta \lg dp + \varepsilon_{4t}$
FPE= 4.51x$(10)^{-4}$

8. 5 Long-Run Relationship

We have used the Granger representation theorem to test for causality in both the short-run and the long-run. Cointegration tests are reported in Table 8.13 and suggest that the two variables are cointegrated, even though the null hypothesis (1) cannot be rejected at the 0.01 significance level. We thus have estimated a *VEC* system with two time lags, as suggested by the information criteria of Table 8.9.

Table 8.13 Johansen cointegration tests

	Null hypothesis (1)	*Null hypothesis (2)*
Lags	$r \leq 1$	$r=0$
1	10.86	42.23
2	10.49	32.14
3	13.18	32.58

The test is based on the hypothesis of no deterministic trend in the data. The sample size is 1955-1991 as for the causality tests. r= number of cointegrating vectors The 0.05 critical values are 9.24 and 19.96 respectively for hypothesis (1) and hypothesis (2).

The results show that output growth causes investment growth both in the long-run and in the short-run, while investment affects output in the long-run only at the 0.15 significance level.

Table 8.14 Granger causality in the augmented *VAR* representation *(k=2)*

	Output→Investment	
$\delta_3=0$	$\delta_{2i}=0$	$\delta_{2i}=0,\ \delta_3=0$
$F_1=7.67$	$F_2=9.35$	$F_3=6.26$
	Investment→Output	
$\delta_7=0$	$\delta_{6i}=0$	$\delta_7=0,\ \delta_{6i}=0$
$F_4=2.22$	$F_5=0.19$	$F_6=0.76$

*no constant is included in the VEC specification. The implied VEC is

$$\Delta z_t = \sum_{i=1}^{k} \delta_{1i} \Delta z_{t-i} + \sum_{i=1}^{k} \delta_{2i} \Delta x_{t-i} + \delta_3 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{1t}$$

$$\Delta x_t = \sum_{i=1}^{k} \delta_{5i} \Delta x_{t-i} + \sum_{i=1}^{k} \delta_{6i} \Delta z_{t-i} + \delta_7 (z_{t-1} - \delta_4 x_{t-1}) + \varepsilon_{2t}$$

The dynamic response of output growth rate to an investment shock is described by the impulse response functions of Figure 8.1 and 8.2, which may be compared with those presented in section 5.5.3.[6] The impact of an investment shock is confined to the short-medium term, as suggested in the estimates for the US economy and in Jones (1995), and is very weak as one could have expected from looking at the non significant impact of lagged investment growth in the *VAR* specification of output growth.

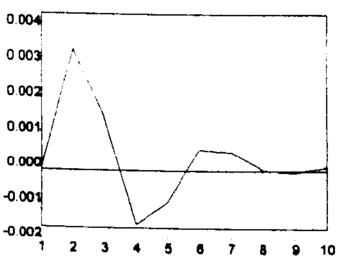


Figure 8.1

We do not present the impulse response function corresponding to the *VEC* specification because of the non robust evidence of cointegration between the two variables. It is worth underlining, that in this specification too the lagged values of investment growth are insignificant in the equation which specifies output growth.

[6] In the *VAR* specification we have adopted the order of the variables following the results of the Granger causality test, and, hence, output growth rate is ordered before investment growth rate.

8.6 Conditional Granger Causality (R&D, Investment, Output Growth)

In order to compare the results of the causality tests with those of the US economy we have considered the augmented version presented in section 6.7. We have thus estimated a *VAR* system with three variables, i.e., investment, output and R&D and tested the significance of the autoregressive component in each equation.

The results are shown in Table 8.15 and confirm that the only clear and significant causal link runs from the output growth rate to the investment growth rate, excluding any other causal relationship.

Table 8.15 Conditional Granger Causality tests in a two and lag *VAR* specification

R&D→Investment	*Output→Investment*	*Investment→R&D*	*Output→R&D*
$F_{2,31}$= 0.04	$F_{2,31}$= 2.42	$F_{2,32}$= 1.81	$F_{2,32}$= 1.87

Investment→Output	***R&D→Output***
$F_{2,31}$= 0.48	$F_{2,31}$= 0.016

Critical value = 2.94 (0.05 significance level)

Testing for cointegration enables us to select a vector error correction model with two time lags. Results are presented in Tables 8.16 and 8.17.

Table 8.16 Johansen cointegration tests

	Null hypothesis (1)	*Null hypothesis (2)*	*Null hypothesis (3)*
Lags	$r \leq 2$	$r \leq 1$	r=0
2	6.28 0.05 c.v. 9.24	18.93 0.05 c.v. 19.96	43.78 0.05 c.v. 34.91

The test is based on the assumption of no deterministic trend in the data.
The sample size is 1955-1991as for the causality tests. r= number of cointegrating vectors.

and the implied *VEC* is :

$$(8.2)\quad \Delta z_t = \sum_{i=1}^{k}\delta_{1i}\Delta z_{t-i} + \sum_{i=1}^{k}\delta_{2i}\Delta x_{t-i} + \sum_{i=1}^{k}\delta_{3i}\Delta y_{t-i} + \delta_4(z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{1t}$$

$$(8.3)\quad \Delta x_t = \sum_{i=1}^{k}\delta_{7i}\Delta x_{t-i} + \sum_{i=1}^{k}\delta_{8i}\Delta z_{t-i} + \sum_{i=1}^{k}\delta_{9i}\Delta y_{t-i} + \delta_{10}(z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{2t}$$

$$(8.4)\quad \Delta y_t = \sum_{i=1}^{k}\delta_{11i}\Delta y_{t-i} + \sum_{i=1}^{k}\delta_{12i}\Delta z_{t-i} + \sum_{i=1}^{k}\delta_{13i}\Delta y_{t-i} + \delta_{14}(z_{t-1} - \delta_5 x_{t-1} - \delta_6 y_{t-1}) + \varepsilon_{3t}$$

Table 8.17 Conditional Granger causality in the augmented *VAR* representation *(k=2)*

	Output→Investment	
$\delta_4=0$	$\delta_{3i}=0$	$\delta_4=0,\ \delta_{3i}=0$
$F_1=5.54$	$F_2=7.09$	$F_3=4.73$
	R&D→Investment	
$\delta_4=0$	$\delta_{2i}=0$	$\delta_4=0,\ \delta_{2i}=0$
$F_4=5.54$	$F_5=0.32$	$F_6=1.88$

	Output→R&D	
$\delta_{10}=0$	$\delta_{9i}=0$	$\delta_{10}=0,\ \delta_{9i}=0$
$F_1=0.27$	$F_2=0.17$	$F_3=0.12$
	Investment→R&D	
$\delta_{10}=0$	$\delta_{8i}=0$	$\delta_{10}=0,\ \delta_{8i}=0$
$F_4=0.27$	$F_5=0.55$	$F_6=0.70$

	Investment→Output	
$\delta_{14}=0$	$\delta_{12i}=0$	$\delta_{14}=0,\delta_{12i}=0$
$F_1=3.92$	$F_2=0.28$	$F_3=1.31$
	R&D→Output	
$\delta_{14}=0$	$\delta_{13i}=0$	$\delta_{14}=0,\delta_{13i}=0$
$F_4=3.92$	$F_5=0.08$	$F_6=1.40$

The clear causal link between output and investment also emerges in this specification, both in the short-and long-run. The *EC* term is also significant (at the 0.06 level) in the output equation, and this fact confirms the previous finding that investment may eventually cause output only in the long-run, conditional on the inclusion of the R&D variable.

8.7 Conclusions

We have analysed the interaction between investment and R&D on the one hand, and investment and output, on the other. The aim was to analyse the causal links between these variables and to compare the results with the US evidence. This is a crucial issue, as many conclusions which are discussed in the theoretical and empirical literature are mainly based on the US evidence. The analysis we have described in this chapter allows us to conclude that the causal link running from R&D to investment is only confirmed for the US economy. In addition, there is evidence that investment may cause R&D in the UK economy if a vector error correction model is used to test for long-run causality. This result is derived using Engle and Granger's methodology, while the Johansen cointegration tests do not show clear and robust evidence of cointegration between the two variables.

The relationship between investment growth and output growth confirms that the role of machinery and equipment investment in the growth process has been overestimated by endogenous growth models. In the UK economy output growth causes investment growth both in the short and in the long-run, while the opposite relationship is not supported by the data. Investment may cause output growth in the long-run, conditional on the inclusion of R&D in the test equation. This result confirms the US evidence, while the short-run evidence is different in the two economies, in that investment and growth show bi-directional causality in the US.

This evidence underlines the different pattern of the business cycle in the two economies and hence the different impact of real and nominal variables on output fluctuations. These latter variables may have a more important role in the UK compared with the US. Recent business cycle analysis for the two economies (Holland and Scott 1996, 1998) underlines that, contrary to the US evidence, a large component of GDP fluctuations are unpredictable in the UK and they are not Granger caused by a standard list of real macroeconomic variables.

Appendix

Table A1 Data Sources

GDP= Gross Domestic Product.

Source: OECD, National Accounts (Annual Data 1955-1991)

MACEQ= Machinery and Equipment Investment.

Source: OECD, National Accounts (Annual Data 1955-1991)

RDUK= Gross Domestic Expenditure in R&D

Source: OECD, Science and Technology Indicators

The GDP deflator is calculated from the GDP statistics of **the OECD National Accounts, (Annual Data, 1955-1991)**.

LGDP= natural log of real GDP

LMACEQR= natural log of real investment in machinery and equipment (deflated by 1985 GDP deflator)

LRRDUK= natural log of gross domestic expenditure in R&D (deflated by 1985 GDP deflator).

Table A2 Sample Statistics (Mean, Standard Deviation)

Variable	*Mean*	*SD*
lmaceqr	10.567	0.555
lgdp	12.678	0.435
lrrduk	9.876	0.589

CHAPTER IX

9. Conclusions

We have analysed recent developments in new growth theory by focusing on models which incorporate knowledge either in physical or in human capital. In such models the growth rate of the economy depends on the parameters which define individual preferences and the production of knowledge. Typically such models show external effects, with human capital or physical capital being paid less than is socially optimal.

However, this externality is not always needed to generate a non zero endogenous growth rate. In Lucas (1988), for examples, the endogenous growth rate does not depend on the existence of an external effect on human capital. In addition, we have analysed another analytical approach which incorporates a specific sector (R&D) producing knowledge. In such models there is still an external effect, as the aggregate stock of knowledge incorporates previous information derived from other firms' activities.

Knowledge is a non excludable good in such models causing underinvestment in human capital in the R&D sector. The balanced growth rate is determined by the accumulation of knowledge in the R&D sector and by the equilibrium conditions in the economy. A typical result of these models is a scale effect, i.e., the growth rate is positively affected by the size of the economy and particularly by the size of the labour force.

We have also underlined other points of controversy of endogenous growth models, which deal with the treatment of knowledge as a production input, the role of institutions, the representation of the R&D sector, and the absence of any consideration of diffusion phenomena.

In the third chapter we have analysed the theoretical background of diffusion models focusing on so-called integrated models, i.e., those models which consider both the demand and supply sides of new technologies. These models are used to incorporate diffusion into an aggregate growth model. We considered such a reformulation of an endogenous growth model in the fourth chapter, by including the diffusion process in a modification of the Romer (1990a, 1990b) model.

The interaction between the sector producing final output and the sector producing capital goods generates the time path of diffusion and hence the growth rate of the economy.

As diffusion proceeds, the growth rate converges to its balanced growth level which is determined by the parameters characterising the diffusion of new capital goods. This implies that a faster diffusion path derived from a shift in the demand for producer durables can affect the long-run growth rate of the economy. This is a new finding within the literature on R&D endogenous growth models.

We have then considered the empirical implications of the theoretical models analysed in chapters two and four. One of the most controversial issues in the empirical literature (which derives from the assumption of the theoretical models) is whether there is a causal link between investment and R&D, on the one hand, and investment and growth on the other hand.

Such a link derives from the interaction between the sector producing capital goods and the R&D sector, for the latter sells blueprints to the former to produce new producer durables. An implicit causal link running from R&D to investment can be hypothesised, in that producing new designs in the R&D sector precedes firms' investment decisions. Investment in new machinery and equipment can then affect output through the typical Keynesian multiplier effect.

One crucial issue is whether a change in investment has a long-run effect on growth or, instead, is this effect transitory or at least confined to the short-run. The empirical literature has mainly focused on causality tests based on data sets which include large samples of countries over the post World War II period. However, these tests do not properly take into account both the short-run and the long-run relationships between the variables. We have instead considered a test procedure which allows us to analyse both the short-run and the long-run properties of the variables using cointegration techniques on time series data for the US and UK economies.

The results suggest that R&D Granger causes investment in machinery and equipment only in the US economy. However, there is evidence of long-run feed-back implying that investment may also affect R&D. This evidence is confirmed using both time series and panel data (which includes almost 20 manufacturing sectors of the US economy over the period 1973-1991). In the UK economy there is no evidence for R&D causing investment nor is there strong evidence of long-run feed-back between the two variables. This suggests that the causal link between R&D and investment may not be thought of as a stylised fact of industrialised economies (as may be deduced from previous empirical investigations).

We have also analysed the relationship between investment and output growth to test whether investment may be considered as the key factor in the growth process. The empirical literature is mainly based on cross-sectional analysis emphasising the role of machinery and equipment investment in the growth process. However, time series investigations on this issue are also necessary to verify the hypothesis and we find little support for the cross-sectional evidence that investment has a long-run effect on growth. In addition, causality tests support bi-directional causality between these variables in the US economy while in the UK economy, output growth causes investment both in the short-run and in the long-run.

In addition, we have considered impulse response functions to verify the impact of an investment shock on output growth. The impact is confined to the short and medium term in both economies, thus rejecting the conclusions of previous models which assume a long-run effect of investment on output growth.

We have also considered the dynamics of R&D, investment and output growth simultaneously, by specifying a trivariate *VAR* model where causality is tested conditional upon the inclusion of a third variable. In the US economy causality running from R&D to investment is reinforced suggesting that this finding is robust to different specifications. The long-run specification of this model suggests that R&D and investment may have a long-run effect on output growth if they are considered simultaneously. This result is partially confirmed in the UK economy, in that investment may cause output growth in the long-run conditional on the inclusion of R&D in the test equation.

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