Do Technology Spillovers Matter for Growth?

Marieke Rensman and Gerard H. Kuper
CCSO and Department of Economics, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands, Tel: (+31) 50 3633756, Fax: (+31) 50 3637337, Email: M.Rensman@eco.rug.nl and G.H.Kuper@eco.rug.nl.

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Abstract: This chapter attempts to explain the growth of labour productivity by (inter)national spillovers from R&D and patenting. We develop a model that is tested for Germany, France, the United Kingdom and the United States of America using a new set of panel data for the period 1955 until 1991. The results indicate that domestic R&D has an indirect and, for Germany, a positive impact on productivity growth.

1. INTRODUCTION

This chapter aims to explain differences in growth rates of labour productivity across countries and over time by changes in technological knowledge. Both formal economic theorists and empirical scholars have always been interested in explaining economic growth, because it affects the standards of living. On the empirical side, economic historians like David (1991), Mokyr (1990) and Abramovitz (1991) are convinced that technology plays a crucial role in explaining modern economic growth since the First Industrial Revolution around the turn of the 18th century. In their opinion, technological progress is a path-dependent process, as it involves a learning and feedback mechanism which depends on the specific characteristics of the economy (Abramovitz, 1991). Furthermore, they found that the diffusion of knowledge throughout the economy takes place only gradually (Salter, 1966) and that it varies across countries and over time (Gerschenkron, 1962).

A second group of empirical scholars are the growth accountants like Denison (1967) and Maddison (1995a). They try to calculate the contribution of various economic factors, such as capital accumulation, on productivity growth using a Solovian type of growth model. The unexplained part in this model, the so-called Abramovitz Residual or Total Factor Productivity, is sometimes labelled as “technical change” (Solow, 1957). Growth accounts thus deal with technology as a purely exogenous variable. This does not help to assess the role of technology in growth (Aghion and Howitt, 1998, p.415-416). Therefore a part of the productivity growth differences cannot be explained within the growth accounting framework, and the residual remains a “measure of our ignorance” (Abramovitz, 1991).

In contrast, modern endogenous growth models attempt to endogenize technology. They explain international growth differences by differences in deliberate efforts to develop new products and technology. Dixit and Stiglitz (1977), Judd (1985), Romer (1990), Grossman and Helpman (1990, 1991), Aghion and Howitt (1998) and others contributed to the development of models in which imperfect competition with innovation-based growth combined with learning-by-doing results in spillovers from industrial research. These spillovers drive a wedge between private and social returns on Research and Development (R&D). This is an approach which according to Solow

> “... has an air of promise and excitement about it...” (Solow, 1994, p.52),

since it models the interaction between technological change and labour productivity growth. Most of this research is based on Schumpeter’s notion of creative destruction in which new technologies takes the place of existing technologies.

The contribution of this chapter is twofold. First, it gives an explicit application and estimation of an endogenous growth model at an aggregate level. Second, it uses a new data set in which the time series of the variables are internationally comparable. This chapter is organised as follows. Section 2 gives an overview of previous efforts to estimate the contribution of technological change to productivity growth. The subsequent section is theoretical in nature and focuses on the importance of knowledge accumulation for long-run sustainable growth. In that section we develop the benchmark model of growth and trade in which technology drives growth. Section 4 describes the construction of the data, while Section 5 presents and discusses the estimation results. Section 6 concludes.

2. A REVIEW OF SPILLOVER STUDIES

Notwithstanding the encouraging development in formal theory, the empirical basis of the new growth models is still very thin. Various authors already tried to estimate the contribution of R&D to productivity, either in levels or in growth rates and both at the micro and macro level. These studies use different methodologies and data, so that the outcomes are diverse and comparison is difficult. We will concentrate on the various results and focus on international spillovers between industrialized countries. The subject of international spillovers is interesting as knowledge diffuses, however not necessarily evenly, across national borders by nature (Keely and Quah, 1998, p.24). However, much of the literature deals with intranational spillovers, *i.e.* inter- and intra-industry spillovers within a country. Examples are micro- or meso-level studies like those by Wolff and Nadiri (1993). The interest in international spillovers revived after Grossman and Helpman (1991) emphasized the importance of openness and the distinction between international and intranational knowledge flows.

Recently, the idea of geographical localization as applied in, for instance, Jaffe *et al.* (1993) comes to the forefront again. However, evidence for international spillovers remains relatively weak. Some authors even argue that intranational spillovers exceed international spillovers significantly. Lichtenberg (1992), for instance, finds that there are no complete, or no instantaneous international R&D spillovers. Branstetter (1996) estimates intranational spillovers (which exceed international spillovers) using microlevel data. He shows that technological externalities can generate multiple equilibria and that growth differences persist. This he considers to support the assumptions of endogenous growth theory.

Despite the mixed results, the evidence tends to confirm the existence of international spillovers. Many studies conclude that the contribution of foreign R&D to domestic productivity is large. In a highly influential article, Coe and Helpman (1995) find that, in a sample of 22 countries, both domestic and foreign R&D contribute significantly to TFP growth. Moreover, foreign R&D is becoming increasingly important, especially for smaller countries. Finally, Coe and Helpman estimate large differences between world-wide and own rates of return of R&D for the G7-countries: about one quarter of the returns from R&D in these countries accrue to their trade partners. These results are not undisputed, however. According to Keller (1997a) the composition of imports, a measure that is used by Coe and Helpman, plays no particular role in estimating positive and large spillovers. He argues that this does not imply that diffusion of embodied technology is not trade-related. In another paper, Keller (1997b) models general spillovers versus trade-related spillovers from R&D. He calculates that 20 per cent of productivity growth due to foreign R&D is channelled through international trade. He also finds that the contribution of foreign R&D varies across countries, and that a country's own R&D is more important than that of the average foreign economy. Finally, Keller tries to disentangle embodied and disembodied technology, but this appears to be difficult to do. Technology can be embodied in traded goods and intermediates, but can also flow disembodied as blueprints or ideas via investments, or via international communication networks. In his opinion, these alternative channels, such as Foreign Direct Investment (FDI), should be included in the analysis.

Lichtenberg and Van Pottelsberghe (1996) include both inward and outward FDI flows. The outward FDI flows are considered to proxy for technology sourcing, which is often done by multinationals. Using part of the sample of Coe and Helpman (1995) and employing an alternative weighting scheme for foreign R&D, Lichtenberg and Van Pottelsberghe (1996) find that domestic R&D is important, especially for the larger countries. This is similar to the result of Coe and Helpman, but the elasticities to output are lower. With respect to foreign R&D, imports and technology sourcing play a significant role while inward FDI does not. The latter result may be explained by the fact that multinationals are aiming for own benefits and not for international technology transfer per se. The rates of return on foreign R&D are very high. Finally, the impact of technology sourcing for many industrialized countries runs through the American R&D stock rather than via imports from the USA.

On the industry-level, Bernstein and Mohnen (1998) examine R&D intensive sectors in the USA and Japan and estimate their effects on each other's production structure and productivity. Over a short period of time, R&D appears to be complementary to international spillovers for both countries. However, over a longer period the results tend to differ between the USA and Japan, with Japan's R&D intensity decreasing. Furthermore, American R&D affects the productivity growth of Japanese industries more strongly than the other way around: 60 per cent of the productivity growth in Japan is attributable to the American R&D, whereas it is 20 per cent in the opposite case. Finally, private returns amount to about 17 per cent in both countries and the social rates of return appear to be even 3,5 to 4 times higher. These private returns to R&D are not out of line as can be seen from Nadiri's (1993) overview of empirical studies on rates of return to R&D.

Similar to Lichtenberg in his 1992-article, Park (1995) distinguishes between government and private R&D. Park uses a panel data set (10 OECD countries over the period 1970-1991) instead of cross-country data. Furthermore, Park calculates the size of two kinds of spillovers, namely spillovers into production and spillovers into research. Foreign R&D appears to spill over via the domestic production function to productivity growth. This result is independent of whether the USA is included into the sample or not. However, the effect of foreign R&D on domestic R&D is only observed when American R&D is included. This is not surprising, as the USA carries out the bulk of world R&D. Like Lichtenberg (1992), Park (1995) concludes that once foreign private R&D is accounted for, foreign government-funded R&D is insignificant to productivity growth. However, foreign public R&D affects productivity growth indirectly via domestic private R&D, as public R&D is often basic research which does not have a direct impact on rates of growth.

Nadiri and Kim (1996) analyse the effect of R&D spillovers on TFP growth in the seven largest economies (G7) in the period 1965-1991. They criticize Coe and Helpman (1995) and Park (1995) in that they are not able to distinguish the productivity effect of R&D spillovers from the factor bias effect. The former occurs because R&D spillovers affects production costs, the latter accounts for the effect of R&D spillovers on the other factors of production. Furthermore, Nadiri and Kim account for country-specific effects. The results indicate that benefits from spillovers differ across countries, where domestic R&D is relatively important for the USA. International knowledge spillovers from the USA to other countries is sizeable, whereas less strong spillovers occur from those countries to the USA, with some exceptions (Canada and Japan). It seems that the USA acts as the technology leader. In narrowing the productivity gaps during the period under consideration, the international spillovers appear to have played a minor role. Furthermore, capital and R&D spillovers appear to substitute each other, while domestic R&D and international spillovers complement each other. Nadiri and Kim (1996) conclude that not only trade, but also the absorptive capacity of a country to utilize foreign knowledge is crucial.

Other studies do not focus on R&D, but on (international) patenting activity as a measure of knowledge accumulation and diffusion. Keely and Quah (1998) argue that intellectual property rights, as a patent system, can provide ex ante economic incentives although they generate ex post inefficiencies (p.16). However, the exact nature of the relationship between patents on the one hand and productivity and R&D on the other hand is not completely understood. An appropriate approach would be to consider patents as an output of the invention process generated by private R&D (Keely and Quah, 1998, p.21-22). An empirical study with patent data is that of Eaton and Kortum (1996). They argue that R&D expenditures are inputs in the innovation process while patents are an indirect measure of research output, and

> “...where patent protection is sought reflects where inventors expect their ideas to be used” (Eaton and Kortum, 1996, p.252).

Eaton and Kortum (1996) use a cross-section of 19 OECD countries to estimate a simultaneous equations model. The data they use to estimate international diffusion are data of patent applications for the year 1988 in the 19 OECD countries. The patent applications are subdivided into the country of origin of the inventor. They conclude that the levels (instead of the growth rates) of productivity explain a country's ability to adopt or innovate. Furthermore, international diffusion rates are about half of the domestic diffusion rates on average. They also estimate that the contribution of the USA to productivity growth world-wide is sizeable, followed in size by Japan and Germany. Germany affects European economies relatively strongly, whereas Japan's influence is observable elsewhere. Notwithstanding the high rates of diffusion, barriers (*e.g.*, in the institutional area) are still large enough to let productivity differences persist. Finally, it appears that human capital (in the form of education and research scientists and engineers) is crucial for the ability to adopt, in addition to trade links and distance (or geographical localization). The importance of human capital and learning is thus confirmed again (see for instance, Benhabib and Spiegel, 1994). The results on trade supports the outcome of the study by Coe and Helpman (1995) mentioned earlier. In another study using cross-section data, Eaton and Kortum (1997) also include research (in particular, research employment) into a growth model in addition to patenting activity in order to explain productivity differences. This is a new step forward as the studies discussed above do not incorporate both variables. Their results indicate that foreign research is two-third as potent as domestic research. Furthermore, the USA and Japan together are again driving the bulk of growth in the sample (of five large industrialized countries).

To summarize, empirical studies on labour productivity growth and technology produce various outcomes. Some of them estimate reduced form equations or growth regressions in which technology is exogenous. Caballero and Jaffe (1993) explicitly apply an endogenous growth model using patent data. However, they do not consider international diffusion. The challenge is to develop and test models that are capable of explaining processes of growth and international spillovers. The mixed results of empirical studies on economic growth

> "...clearly underlines the need for growth economists to devote more time to the construction of data..." (Crafts, 1997, p.60),

because the results of these studies are sensitive to the data used. For the construction of proxies of the economic variables in the model, we constructed a new data set for the USA, UK, France and Germany, and present the resulting time series in Section 4. A detailed description of the construction and the sources of the data is provided in the appendix.

3. MODEL

In this section, we formulate a model with international technology spillovers and catch-up. The empirical studies discussed in Section 2 give a handle on important research subjects. First, international technology spillovers do take place and flow through different channels such as trade and foreign direct investment. But these spillovers are, in general, not complete. So growth differences will persist (Keely and Quah, 1998, p.26). Nevertheless, spillovers from abroad seem to affect economic growth. Besides, technology flows within a country (intranational spillovers) also play a role in explaining productivity growth.

Second, both patenting activity as a proxy for knowledge flows and R&D expenditures should be incorporated into an empirical growth model. Cameron (1996) and Temple (1999) argue that in empirical applications the Aghion and Howitt model needs to be extended with knowledge spillovers from other countries. In this chapter we proxy these spillovers by patents. Some studies discussed above indicated that domestic R&D is crucial in order to be able to absorb new foreign technology. One of the results in our estimations in Section 5 is that domestic R&D works indirectly on productivity growth: a country needs a certain knowledge basis in order to be able to adopt and learn from new knowledge from abroad in the form of patents. Thus we may consider R&D expenditures as the input in the innovation process and patents as the output (see Griliches, 1990). Note that the R&D expenditures are privately-funded (business enterprise R&D). The differences in patenting activity in the various countries can indicate whether the national technological state of the art enables a country to catch up with the “technological leader”, which in our case is the USA. Moreover, some studies indicate that R&D in the USA affect other economies’ productivity growth significantly, but not evenly across countries. We thus also account for country-specific effects in our empirical research.

The model we use here draws heavily on Aghion and Howitt (1998, Ch.12) and it is driven by product differentiation, quality improvements and research spillovers. The underlying theory allows new intermediate products to open up, as in Romer’s horizontal innovations model (Romer, 1990), which are then subject to quality improvements as in Young’s vertical innovations model (Young, 1998). In order to test the model using aggregate data, it is shown that, with some convenient assumptions, the production function on the aggregate level can be written as a Cobb-Douglas production function. We discuss the underlying theoretical structure of the model in detail in the appendix and discuss technological progress and the role of spillovers in some more detail below.

3.1 Production and capital

On the aggregate level, there is a stock of capital K_t embodied in machines. New capital is produced at rate I_t. Gross investment I_t, consumption C_t and research N_t are produced by labour L_t and intermediate goods x_{it}:

$$Y_t = C_t + I_t + N_t = Q_t^{\alpha-1}\left[\int_0^{Q_t} A_{it} x_{it}^{\alpha} di\right] L_t^{1-\alpha} = A_t L_t k_t^{\alpha}.$$

Variable k_t is defined as the capital stock per efficiency unit of labour $K_t/(A_tL_t)$, where A_t indicates the average productivity of the economy, and Q_t is the number of intermediate goods that have been created in i industries.[1] The flow of intermediate products is such that the ratio of Q over L is constant. Capital-market equilibrium and the production function of final output produce the aggregate Cobb-Douglas production function. Finally, defining g_t as the growth rate of labour productivity $\Delta \ln Y_t - \Delta \ln L_t$, the basic equation in rates of growth is

$$g_t = g_{A,t} + \alpha \frac{dk_t / dt}{k_t}. \qquad (1)$$

The second term on the right-hand side of equation (1) is the rate of growth of output per efficiency unit of labour $f(k_t)$, where

$$\frac{dk_t / dt}{k_t} = \frac{dK_t / dt}{K_t} - \left(g_{A,t} + g_{L,t}\right).$$

Assuming a constant rate of depreciation of capital goods δ, and defining i_t as I_t/K_t. this can be written as:

$$\frac{dk_t / dt}{k_t} = i_t - \left(\delta + g_{A,t} + g_{L,t}\right). \qquad (2)$$

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[1] A sector in this model is defined as a certain kind of activity, such as doing R&D, producing intermediates or final goods, carried out by an agent. The term sector is sometimes used in a different sense, for instance in multi-sectoral models, in which each good or intermediate i is produced in sector i. Here we prefer the term industry. In empirical studies, a sector is part of the economy, such as the manufacturing sector, or at a lower level, industries.

3.2 Technological progress

In the R&D sector of each industry, innovations of size σ occur at a rate ϕ_t with a probability as determined by a Poisson distribution. These innovations add to the stock of knowledge. The arrival rate reflects the probability of a researcher to innovate the next blueprint for intermediate good *i* which replaces the existing technology. The "leading-edge technology parameter", defined as the technology used by the "technological leader", grows at rate

$$g_{\hat{A},t} = \frac{d\hat{A}_t / dt}{\hat{A}_t} = \sigma\phi_t \,.$$

The technology of follower countries will evolve by own R&D efforts and by technology spillovers from the leading country to the followers. This may be interpreted as a limiting case of a more general model with mutual technology spillovers (see Aghion and Howitt, 1998, p.421). The arrival of new blueprints will gradually replace existing average technology A_t with the leading-edge technology. So, the long-run change in productivity dA_t/dt equals the arrival rate of innovations times the average change of technology:

$$\frac{dA_t}{dt} = \phi_t\left(\hat{A}_t - A_t\right)$$

or

$$g_{A,t} = \frac{dA_t / dt}{A_t} = \phi_t\left(\frac{\hat{A}_t}{A_t} - 1\right) = \phi_t\left(\Omega_t - 1\right). \qquad (3)$$

We may label Ω in equation (3) as the technology gap of the follower with the leader country. We assume that Ω converges to a constant, say $1+\sigma$. This implies that in the long run:[2]

$$g_{\hat{A}} = g_A \,.$$

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[2] Note that in the long run when $g_{\Omega}=0$, $\Omega=1+\sigma$.

3.3 Empirical specification

Above it was assumed that the flow of innovations depends on the arrival rate of innovations and the change of technology. In the remainder of this section, we take a bit different approach to arrive at a testable specification given the data available. In the process, inevitably, we have to make some ad hoc assumptions.

Suppose, there are m countries each with its own level of technolgy A^j. We define the leading-edge technology as:

$$\ln \hat{A}_t \equiv \sum_{j=1}^{m} \omega^j \ln A_t^j \ ,$$

where ω^j is the importance of country j as a source of new technological ideas for other countries, and $\Sigma_j \ \omega^j = 1$. Suppose that country k is the technological leader, then $\omega^k = 1$. The weighting scheme ω^j needs to be known a priori, and it is assumed that for the countries considered here, the USA is the technological leader.

As before, it is assumed that, in the long run, the technology gap converges to a constant, that is[3]

$$-\ln \Omega^j = \ln A_t^j - \ln \hat{A}_t = z^j \ .$$

This implies that, in the long run the growth rates of the technologies of the leader and the followers must be equal:

$$g_A^j = g_{\hat{A}} \ .$$

Now suppose that the change in the level of technology in country j depends on the technological gap with the leader:

$$g_{A,t}^j = \Delta \ln A_t^j = -\lambda_t^j \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j \right) + \beta g_{\hat{A},t} \ , \qquad (4)$$

where the term between brackets on the right-hand side of equation (4) is the gap. The last term is the rate of growth of the technology of the leader country. Above we noted that in the long-run, when the gap is constant, we expect β to be equal to 1.

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[3] Note that for follower country j, $0<\Omega^j<1$, so that $z^j<0$.

Equation (4) is the empirical counterpart of equation (3) above. Parameter λ^j measures the speed of convergence of country *j*'s technology to the leading-edge technology. We loosely assume that the speed of convergence is influenced by own R&D:

$$\lambda_t^j = \lambda + \gamma \Delta \ln n_t^j , \tag{5}$$

where n^j reflects R&D productivity. This captures the notion of the theoretical arrival rates of innovation. The idea is that in order to adapt foreign technology, more R&D is needed to upgrade the skill-level of workers. It is likely that γ is positive, since doing R&D increases knowledge, either intentionally or by coincidence. Other factors than R&D that may attribute to the process of adjustment are simply captured by the constant term λ in equation (5). One can think of organisational and managerial factors and knowledge not embodied in own R&D and in patents.

The composite term λ^j as determined in equation (5) is assumed to be positive. If a country *j* lags behind in terms of technology, then a positive value for λ^j signals convergence to the leading-edge technology. For practical purposes we quantify technology A^j by the number of patents and the reciprocal of R&D productivity by the ratio of R&D expenses D^j over GDP Y^j (*cf*. Aghion and Howitt, 1998, p.418):

$$n_t^j \equiv \frac{D_t^j}{Y_t^j} .$$

3.4 The system

Above the model is presented. Summarizing, the model consists of the following equations:

$$\begin{aligned}
g_t^j &= g_{A,t}^j + \alpha g_{k,t}^j , \\
g_{A,t}^j &= -\lambda_t^j \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j \right) + \beta g_{\hat{A},t} , \\
\lambda_t^j &= \lambda + \gamma \Delta \ln n_t^j , \\
g_{n,t}^j &= g_{D,t}^j - g_{Y,t}^j , \\
g_{k,t}^j &= i_t^j - \left(\delta^j + g_{A,t}^j + g_{L,t}^j \right), \\
g_{Y,t}^j &= g_t^j + g_{L,t}^j .
\end{aligned}$$

The symbols have the following meaning:

A_t^j	the level of technology of country *j*
$\hat{A}_t^j$	the level of technology of the leading country, here the USA
g_t^j	growth rate of labour productivity of country *j* at time *t*
$g_{A,t}^j$	growth rate of technology of country *j* at time *t*
$g_{k,t}^j$	growth rate of physical capital in efficiency units of country *j* at time *t*
$g_{\hat{A},t}^j$	growth rate of leading-edge technology at time *t*, here the USA
λ_t^j	speed of convergence of technology of country *j* at time *t*
$g_{n,t}^j$	growth rate of the reciprocal of R&D productivity of country *j* at time *t*
$g_{D,t}^j$	growth rate of R&D expenses of country *j* at time *t*
$g_{Y,t}^j$	growth rate of GDP of country *j* at time *t*
i_t^j	ratio of investment over capital of country *j* at time *t*
$g_{L,t}^j$	growth rate of employment of country *j* at time *t*

The first equation is the familiar log-linear Cobb-Douglas production function. The second equation describes the development of technological progress, which depends on the technological gap with the leader. The third equation describes the speed at which the technological gap is closed. These equations are the core of the model, the other equations are identities.

Substituting the identities and the convergence process in the first two equations we arrive at two equations, one for the growth rate of labour productivity and one for the growth rate of technology:

$$\begin{aligned} g_t^j &= g_{A,t}^j + \alpha g_{k,t}^j = g_{A,t}^j + \alpha\left(i_t^j - \left(\delta^j + g_{A,t}^j + g_{L,t}^j\right)\right) \\ &= (1-\alpha) g_{A,t}^j + \alpha\left(i_t^j - \delta^j - g_{L,t}^j\right), \end{aligned} \tag{6}$$

$$\begin{aligned} g_{A,t}^j &= -\left(\lambda + \gamma g_{n,t}^j\right) \cdot \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1}^j - z^j\right) + \beta g_{\hat{A},t}^j \\ &= -\left[\lambda + \gamma\left(g_{D,t}^j - g_t^j - g_{L,t}^j\right)\right] \cdot \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1}^j - z^j\right) + \beta g_{\hat{A},t}^j . \end{aligned} \tag{7}$$

Equations (6) and (7) will be estimated, but first we take a look at the data.

4. DATA

Testing formal models of the type presented in the previous section requires accurate data, on for instance physical capital and R&D, which are often not available on detailed level. Moreover, growth economists are interested in *long-run* development for a broad selection of countries in different phases of economic development, but internationally comparable and long time series are not always available. Measurement problems are huge, see for instance Griliches (1994), so we want our model to be as simple as possible.

We constructed proxies for the variables in equations (6) and (7) in order to estimate the effects of technological change on labour productivity growth.

The appendix shows a list of the variables, and the sources of the data used. In the current section, we show the development of the mentioned variables for the USA, UK, France and Germany in the period after the Second World War. Figure 1a on labour productivity in the total economy shows that France caught up with the USA during the period 1955 to 1991, while in 1955 it ranked lowest with Germany. The growth rate of labour productivity in France has always been positive in this period, whereas the other three countries experienced some repercussions (Figure 1b). German labour productivity has also increased fast, but it did not yet succeed in catching up with the USA (at least not until 1991). The Anglo-American gap remained relatively constant during the period under consideration.

Traditionally, physical capital accumulation has been assigned a crucial role in economic development. Growth accountants like Maddison (1995b) devote much time to the construction of data on capital stocks and investment in order to account for the share of capital accumulation in labour productivity growth. Figure 1c displays the growth of gross capital stocks. From Figures 1b and 1c, we can hardly draw unambiguous conclusions on the link between capital accumulation and labour productivity growth. Only the differences in growth rates of the gross capital stock between the countries are clear. Up to the early seventies, Germany experienced high growth rates, whereas in the subsequent decade, the rates of growth for France were larger. The British capital stock grew less rapidly, but in all three economies the growth rates declined over time. The growth rates for the USA are low on the average, but, given the size of the economy, the level of its capital stock is higher. Furthermore, the growth rates suggest that they go up and down with the business cycles, like the growth rates of labour productivity.

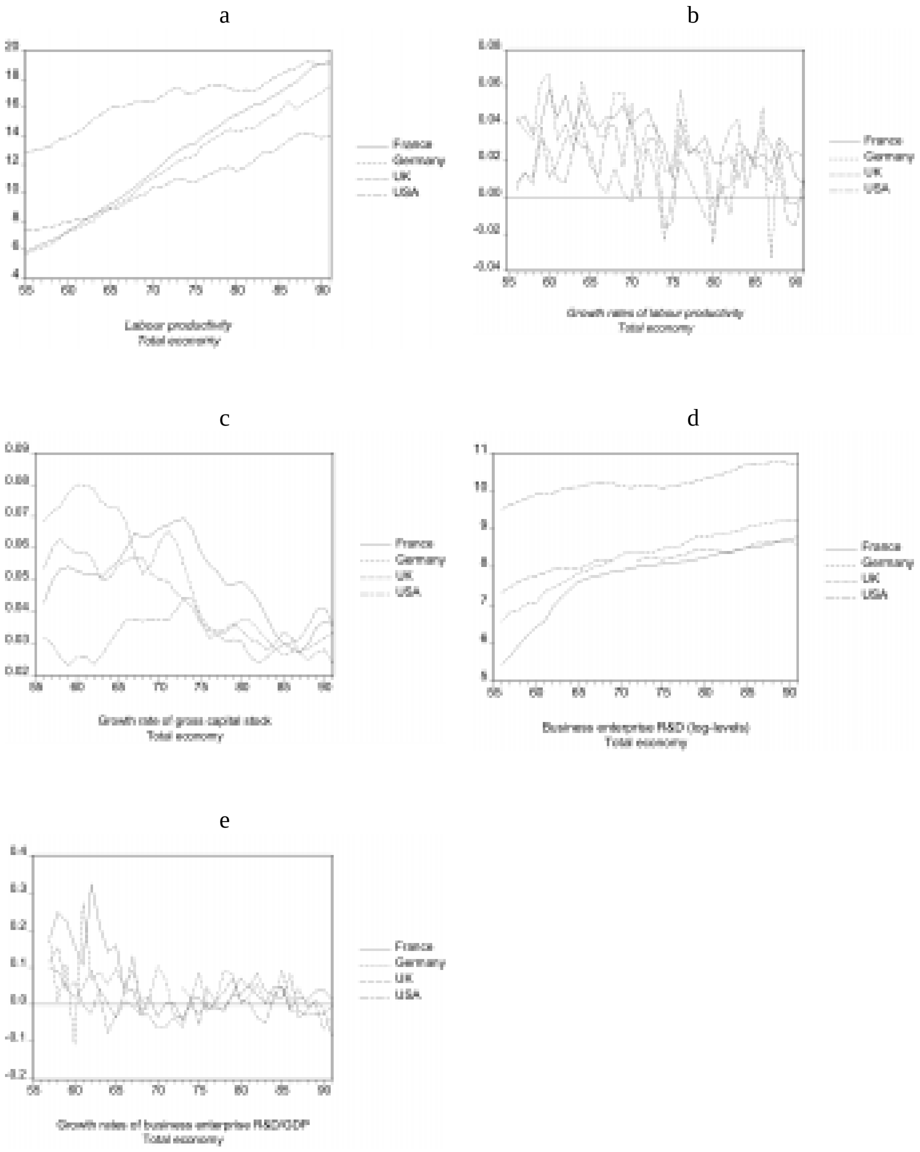

Figure 1. Total economy, 1955-1991

According to endogenous growth models, technological development affects the national growth rates of labour productivity, and thus also differences between countries. Capital accumulation then plays only a supporting role. In our model in Section 3, technology is represented by cumulative experience in creating new knowledge (proxied by business enterprise R&D expenditures) and the speed of convergence towards the leading edge technology (proxied by patent activity). Figure 1e shows the growth rate of R&D expenditures-to-GDP ratio from 1956 to 1991 in total economy. Before 1965, the growth rates of the R&D-to-GDP ratio were high for France, with Germany a good second. Figure 1d shows that the American-British R&D ratio remained relatively constant, while Germany and France caught up to some extent. Especially French R&D grew fast before 1965. The explanation for the fact that the American R&D expenditures did not grow so fast may lie in its early development in this area. Already before the 1950s, the USA was the first Western country to start with systematical R&D. Furthermore, the pattern of growth in R&D seems to be sensitive to the business cycle.

In Figure 2a, the yearly numbers of applications for patents (applications in short) in each country (both foreign and domestic applications) are presented. Applications for patents are made by inventors to the (inter-) national patent offices. The idea behind the use of data on patents is that they contain technological knowledge. Particularly, patents are the outcome of innovation processes, whether or not starting with formal R&D, and theoretically they should have an impact on labour productivity growth. Grants are those patents (or new knowledge) that will effectively come into use, but grant numbers are often sensitive to bureaucratic procedures at the patent offices. Applications are no patents yet (*i.e.*, grants), but they reflect the possibility in which a country is ready to gain or adopt new knowledge.

The total number of applications represents also an element of international knowledge spillovers. The countries under consideration are trading and communicating with each other, so that their national knowledge is spreading to other countries in some way. This diffusion takes place by trading goods and intermediates, investing abroad (capital flows) or by political and individual networks. Patents applied for by foreigners are also playing a role. In this way a general knowledge pool emerges, which may have a larger effect on the national growth rates of labour productivity than national expenditures on R&D alone.

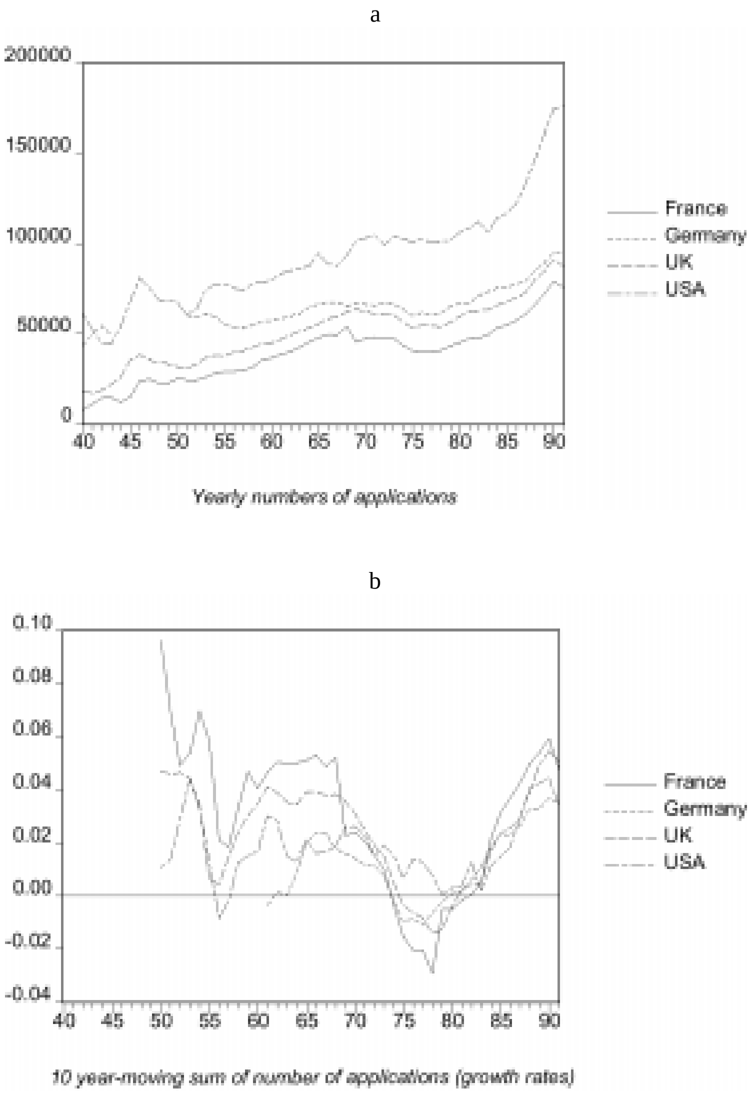

Figure 2. Applications, 1940-1991

Figure 2a shows that, as one may expect, the number of patents applied for in the USA by American and foreign inventors is clearly higher than those in the other three countries. The USA is attractive to patentees as it represents a large, more or less uniform market. It is a market in which most consumers show similar characteristics and demands, so that scale effects from production based on new technology can be exploited very well and one may expect certain profits. Furthermore, a nation's total number of applications can reflect its relative strength in technology. Particularly, it indicates a country's ability to turn new knowledge locked up in applications into economic growth. In the current chapter, the USA are considered as a "technological leader". The innovative effort of American firms and individuals is significant, although the share of foreigners has increasing during the period. The Anglo-American gap in applications is very large, but France and Germany do not perform much better. The American-German gap has even widened since the 1950s.

However, cumulation of patent numbers over a number of years is supposed to reflect the knowledge level of a country more effectively, as yearly numbers are very sensitive to the business cycle and some bureaucratic problems or measures, such as the change in the international patent law in the 1970s. Furthermore, we assume that patents from years ago will need time to come into use as the knowledge incorporated in the patent will have to be made concrete in products or production processes. So patents of, for instance, 10 years ago can still have impact on today's economic performance.

Figure 2b displays the time series on the growth rates of the 10-year moving sum of the number of applications in each country. All series show a clear trend, with a decline starting already in the 1960s. The lowest point is reached somewhere between 1975 and 1980. The French growth rates are fluctuating relatively strongly, whereas the American rates are on average lower than those of the other countries.

5. EMPIRICS

In Section 3 the model is presented and the equations are derived. Here we repeat the equations that are estimated. The first equation is the log-linear Cobb-Douglas production function:

$$g_t^j = (1-\alpha) g_{A,t}^j + \alpha\left(i_{t-1}^j - \delta_{t-1}^j - g_{L,t-1}^j\right).$$

We lagged the investment term to obtain a statistically significant effect of investment on per capita income. Such a lag may be theoretically explained by a "time-to-build" argument: it takes some time for investment to become productive. This equation is estimated with iterative weighted least squares, where lagged productivity growth is added as an instrument. The second equation describes the development of technological progress, which depends on the technological gap with the leader:

$$g^{j}_{A,t} = -\left(\lambda + \gamma\left(g^{j}_{D,t} - g^{j}_{t} - g^{j}_{L,t}\right)\right)\cdot\left(\ln A^{j}_{t-1} - \ln \hat{A}^{j}_{t-1} - z^{j}\right) + \beta g^{j}_{\hat{A},t}\ .$$

This equation is estimated using iterative SUR.

Both equations are estimated on a panel of annual observations. The countries considered are France, Germany, the United Kingdom and the United States of America. The time period considered is 1957-1991. The interesting parameters are the capital share in output α and, more importantly, the parameters in the technological progress function: the R&D effect on adjustment λ, the non-R&D effect on adjustment γ and the long-run technology gap z.

5.1 Estimation results

From the estimation results presented in Table 1 we can draw the following conclusions. First, the fit is not particularly good, especially not for the productivity equation. However, the capital share is 0.21 which seems reasonable. Second, most parameters are significant at a 5% significance level, and all parameters have the expected sign.

More important are the estimations for the technology function. Here, we present three versions: one equation with a common R&D effect λ and a common non-R&D effect γ for all countries considered (the first column in Table 1). The second equation (second column) allows the non-R&D effect to differ between countries, while the third equation (third column) allows both the R&D effect and the non-R&D effect to differ between countries. From the results we can conclude that own R&D significantly affects the speed at which countries adapt foreign technology for Germany only. For the UK and France own R&D seems to be less important. Other, non-R&D, factors seem to play a significant role in the adjustment process. These factors matter for all countries considered. For France and the UK these other factors are more important then own R&D.

Parameters z indicate the long-run technology level with respect to the USA. In the theoretical model these relative technology levels were supposed to be constant in the long run. From the estimation results we can conclude that, in the long run, France has a level of technology of about 51% (calculated from the first column in Table 1 as exp(-0.68)) of that in the USA. For Germany and the UK these numbers are 67% and 63%, respectively. These estimation results more or less are confirmed with the data as can be seen from Figure 3. Note that there are sharp differences in the data for the periods before and after 1970. Before the early 1970s relative technology levels seem to converge, whereas after 1970, relative technology levels more or less stayed constant or even dropped a little compared to the USA.

Table 1. Estimation results, 1957-1991 (t-values between brackets)

		Technology: $g_{A,t}$		
	Productivity: g_t	1	2	3
α	0.21			
	(5.80)			
λ (common)		0.09	0.08	
		(6.63)	(5.95)	
λ France				0.09
				(3.36)
λ Germany				0.12
				(7.81)
λ UK				0.06
				(3.38)
γ (common)		0.12		
		(1.56)		
γ France			0.04	-0.04
			(0.68)	(-0.52)
γ Germany			0.53	0.47
			(3.14)	(2.91)
γ UK			0.01	-0.01
			(0.09)	(-0.20)
β		0.59	0.58	0.58
		(5.66)	(6.34)	(5.50)
z France		-0.68	-0.63	-0.60
		(-19.00)	(-16.63)	(10.11)
z Germany		-0.40	-0.38	-0.37
		(-16.68)	(-21.47)	(-23.50)
z UK		-0.46	-0.43	-0.33
		(-16.44)	(-15.47)	(-4.04)
Observations	136	98	98	98
Adj. R^2				
France	-[a]	0.32	0.31	0.25
Germany	-	0.39	0.34	0.17
UK	-	0.45	0.44	0.39
USA	-	N.A. [b]	N.A.	N.A.
Durbin-Watson				
Adj. R^2				
France	0.246	0.215	0.207	0.192
Germany	0.913	0.216	0.251	0.192
UK	0.719	0.132	0.119	0.105
USA	0.842	N.A.	N.A.	N.A.

[a] negative

[b] not applicable

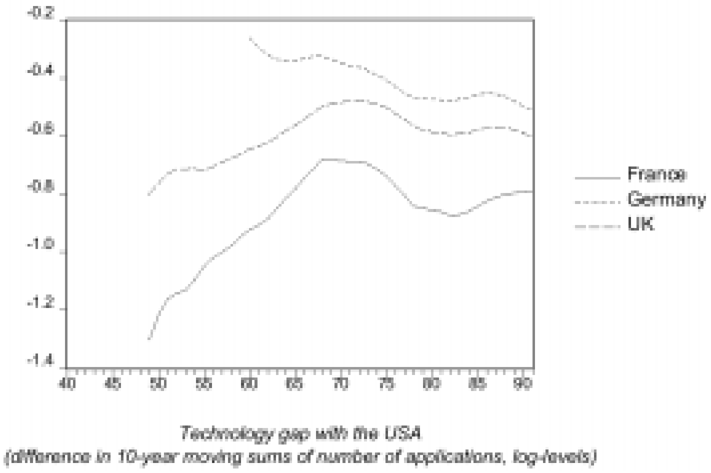

Figure 3. Technology gap vs. USA, 1949-1991

6. CONCLUSIONS

In this chapter we try to explain growth differentials across countries by technological developments. It builds on recent endogenous growth models, which combine imperfect competition with innovation-based growth and learning-by-doing in innovation. These forces generate spillovers from industrial research and patenting activity. Our model is a multi-country, with international technology spillovers and catch-up. The model is tested for the USA, UK, France and Germany using a new set of panel data for the total economy in the period 1956-1991.

From the estimation results we can draw a number of conclusions. First, most of the parameters of interest are significantly different from zero and have the expected sign. Second, technological development in the form of the growth rate of R&D expenditures and the growth rate of the gap with the technological leader USA appear to play a significant role in the explanation of the growth rate of labour productivity. Third, international spillovers do occur between the four countries under consideration, but they do not take place completely and not immediately, so that productivity growth rate differences continue to exist. Four, the growth in R&D expenditures has an indirect and positive effect via the adjustment of the gap with the USA only for Germany. Domestic efforts to gain knowledge thus are important to some countries as a learning mechanism for the adoption of foreign technology locked up in patents from abroad. Five, the diffusion of knowledge from the USA to Germany, France and the UK differs. So, the technological gaps between these countries and the USA also differ, and the growth rates of productivity differ as well. The technology gaps converge over time, implying that knowledge diffuses only gradually and varies across countries, and that learning takes time. Finally, it may be expected (from estimations not included in this chapter) that the results also differ between time periods.

Despite these interesting and intuitively plausible results, one has to bear in mind that formal R&D expenditures and patenting activity do not capture all forms of knowledge. Think of tacit knowledge, which is important in some sectors of the economy. Furthermore, organisational and managerial knowledge are not accounted for explicitly. Human capital accumulation is only implicitly reflected in own R&D efforts, which appeared to be significant for the adjustment process. In order to catch up, a country thus needs a knowledge basis accumulated via learning-by-doing in the R&D process. This argument may be tested if the model is extended with (the effects of) skills. For reference on the complementarity between skills and R&D we refer to, for instance, Colecchia and Papaconstantinou (1996).

To conclude, the results vary across countries, sectors and over time. This is confirmed by other empirical studies (as discussed in Section 2) as well. Crafts argued that ‘

> “... success in ‘technology transfer’ varied and seems to have been affected by institutional and policy differences...” Crafts (1997, p.64).

This corresponds with the concept of “ultimate” causes of economic growth as defined by Maddison (1995a), and is also discussed by among others North (1990), on reducing transaction costs, Abramovitz (1991), on the residual as “our measure of ignorance”, and Olson (1982) on the impact of political systems.

DATA[4]

We have constructed proxies for the variables in equations (6) and (7) for the total economy. The original data used for construction of these proxies are discussed below. Note that total (gross) investment and capital are the sum of non-residential structures and machinery and equipment. Furthermore, the depreciation rate δ was assumed constant in the model discussed in Section 3. However, with help of the data on capital stocks and investments, we made time series on the depreciation rate, which we used in estimation. The proxies used in estimation are:

- the growth rate of labour productivity:

  $$g_t^j = g_{Y,t}^j - g_{L,t}^j \,,$$

  where g_Y and g_L is log-differenced GDP and employment, respectively,
- the growth rate of the reciprocal of R&D productivity:

  $$g_{n,t}^j = g_{D,t}^j - g_{Y,t}^j$$

  where g_D is log-differenced R&D expenditures,
- the growth rate of technology:

  $$g_{A,t}^j$$

  calculated as the log-difference of 10-year moving sum of the number of total applications for patents in country *j*,
- the growth rate of leading-edge technology:

  $$g_{\hat{A},t}^j$$

  calculated as the log-difference of 10-year moving sum of the number of total applications for patents in the USA,
- the level of technology

  $$\ln A_{t-1}^j$$

  calculated as the log of 10-year moving sum of number of total applications for patents in country *j* , lagged one year,
- the level of technology of leading country

---

[4] With special thanks to Bart van Ark (updated production and employment data), Angus Maddison (standardised capital data), Bart Verspagen (updated R&D and patent data), and Jan Luiten van Zanden (national patent office data).

$$\ln \hat{A}^{j}_{t-1}$$

calculated as the log of 10-year moving sum of number of total applications for patents in the USA, lagged one year,

- the growth rate of physical capital in efficiency units as defined in equation (2)

$$g^{j}_{k,t} = i^{j}_{t} - \left(\delta^{j} + g^{j}_{A,t} + g^{j}_{L,t}\right),$$

where i_t is gross investment *I* divided by gross capital stock *K* and

$$\delta^{j}_{t} = \left(I_t - \Delta K_t\right) / K_t \,.$$

Output and employment

Data sources: Van Ark (1996, updated), OECD (1997b).

The time series for GDP are updated (production census) series from Van Ark (1996, Appendix tables 1.2,1.3,1.8,1.9). These series are in constant national prices, but not based on the same years. Table 3.4 from Van Ark (1996) gives the National Account equivalents for the census data in the year 1975 and are constructed in such a way that international comparison is meaningful (*e.g.*, GDP is at factor cost, while the national census series are sometimes at producer or market prices). Using table 3.4, the census series can be re-based to the year 1975. As the data in table 3.4 are in mln US$, the PPPs given in table 3.3 can be used to convert them back into national currencies. The scale factor is the ratio in 1975 of the current value of GDP to the value at prices of the base year in the original series, both in national currencies. After re-basing, the series are converted into PPP in 1975 from OECD (1997b, table 3, p. 162).

In table 3.4 of Van Ark (1996), data are also given for the number of employees for total economy. These data are somewhat different from the census employment data in 1975 (updated series from Appendix tables 2.2, 2.3, 2.8, 2.9), for the same reasons as above, namely that definitions of GDP and employment differ between National Accounts and national census series. Using the 1975 data on employment in both table 3.4 and the census series, employment is re-scaled.

Capital stocks and investment

Data sources: Kravis *et al.* (1982), Maddison (1995b), OECD (1966, 1997b).

Time series for total economy on gross stock of fixed non-residential capital and gross investment in 1990 national currencies at midyear are from Maddison (1995), tables 7 and 8 on Non-Residential Structures (NRS) and Machinery & Equipment (ME). Official data were standardised by Maddison with respect to asset lives and retirement patterns. All asset lives are as closely as possible to those in the USA, *i.e.*, 39 years for NRS and 14 years for ME, and all assets are scrapped when their expected life expires. The data were also corrected for war damage. With the 1990 price index for Gross Fixed Capital Formation (OECD, 1997b, table 34, pp.146-147), the series were re-based to the year 1975. Data on prices before 1960 are indicated by the price index on GNP (OECD, 1966, table on price index of GNP, p. 6). The series were converted with 1975 PPPs calculated on the basis of data in summary tables 6.1

and 6.3 in Kravis *et al.* (1982, p. 167 and p. 179). Following Maddison (1995), the PPPs for NRS are a weighted average of the PPPs for Non-Residential Buildings (lines 111-118) and Civil Engineering Works (lines 119-122), with the weights being their per capita expenditures in national currencies. PPPs for ME are from table 6.3 (lines 123-144). The resulting 1975 PPPs are displayed in the table below.

Table 2. 1975 PPPs for non-residential structures (NRS) and machinery & equipment (ME)

	NRS	ME
UK	0.516	0.539
France	5.341	5.430
Germany	2.404	3.350

Technology indicators

Technology indicators are the most difficult part of the data construction. In the current chapter, R&D expenditure time series and data on patent numbers are applied to proxy the growth of knowledge in the economy.

Research and development
Data sources: OECD (1995b, 1997b), Verspagen (1996, updated).

The time series for Research and Development (R&D) in current national prices for total economy were from updated data of Verspagen (1996). Some gaps in the series of Verspagen (1996) were filled with ANBERD data from OECD (1995b). The OECD data and Verspagen’s data namely do not differ when compared for other years, so that the data may not differ much for the years at which only OECD data are available. After filling the gaps as far as possible, only data for the UK in 1970 and 1971 could not be filled in.

The series are converted for each country into 1975 PPP$ using the 1990 price index for GDP (OECD, 1997b, table 31, pp.144-145) and the GDP PPPs of 1975 in table 3 on p. 162 in OECD (1997b). Special R&D price indices would be preferred, as “such special price indices indicate a higher rate of inflation for R&D than in the economy at large” (OECD, 1984, p. 309). So R&D growth rates calculated from time series converted with GDP indices may appear to be too optimistic. The use of GDP PPPs also reflect the relative purchasing power parities only broadly. Unfortunately, R&D indices or PPPs are not available for the present.

Applications for patents
Data sources: Deutsches Patentamt, I.N.P.I., OECD (1991, 1995a, 1997a), WIPO (1983).

The sources for data on the total number of applications for patents are:

- All countries from 1973 onwards: OECD (1991, table 20) for 1973-1974, OECD (1995a, table 20) for 1975-1987, OECD (1997a, table 73) for 1988-1991.
- France before 1973: I.N.P.I. for 1962-1972; WIPO (1983) for 1940-1961.
- Germany before 1973: Deutsches Patentamt for 1949-1972; WIPO (1983) for 1940-1943.
- UK and USA before 1973: WIPO (1983) for 1940-1972.

MODEL

Consumers maximize utility over an infinite horizon given their budget constraint. They derive utility from a set of differentiated products. Basically the model is a multi-country model. In each country we have three sectors:[5]

1. An R&D sector producing blueprints (or patents) for new products *i* using primary resources and previous accumulated knowledge *A*, home and abroad.
2. An intermediate-goods sector with a total number of Q_t industries. In each industry a monopolist holds a patent to the latest generation of differentiated product x_{it}, and uses capital K_{it} as described in the simple production function for intermediate goods:

   $$x_{it} = K_{it} / A_{it}$$

   Here A_{it} is the productivity parameter of latest version of intermediate product *i*. We assume that successive vintages of the intermediate product are produced by increasingly capital intensive techniques. This implies that productivity A_{it} increases over time. Finally, profit maximizing behaviour implies that all producers of intermediates i supply a common amount of output (see below and Aghion and Howitt, 1998, p. 95).
3. A consumer-goods sector producing final output Y_t using technology, labour L_t and intermediate inputs measured by a Dixit-Stiglitz index of differentiated products:

   $$Y_t = Q_t^{\alpha-1}\left[\int_0^{Q_t} A_{it} x_{it}^{\alpha} di\right] L_t^{1-\alpha}, \qquad 0 < \alpha < 1$$

   where Q_t is the number of differentiated products. Brands x_{it} substitute well for each other: the elasticity of substitution between every pair of available brands $\varepsilon = 1/(1-\alpha) > 1$.

Resources devoted to R&D which improve the quality of existing products (vertical innovations) contribute over time to productivity in the production of final goods as well as to the stock of knowledge. Imitation of ‘old’ products increases the number of differentiated products Q_t (horizontal innovations) but does not add to the social knowledge pool. Although in reality horizontal innovations do occur (increasing variety), the productivity effects of such innovations are not as clear as those of quality improvements. Despite increased possibilities to specialize and satisfying a variety of needs, more variety increases also complexity of production and thereby errors. Moreover, thin-market transaction costs will arise. To sum up, innovation generates growth and imitation spreads the research input over more sectors.

To avoid the scale effect of R&D (doubling the number of workers in research does not double growth rates, see Jones, 1995, and Aghion and Howitt, 1998, p. 404-405), the number of sectors Q_t grows at the same rate as the number of workers L_t , that is L_t / Q_t is constant. Basically, it is assumed that imitation is a serendipitous process. This means that imitation just happens: no one spends resources attempting to imitate. The flow of imitation products can now be written as:

---

[5] In our model, multi-country spillovers only matter in the specification of technological progress, so we introduce the index denoting a specific country when we discuss technological progress.

$$\frac{dQ_t}{dt} = \xi L_t , \qquad \xi > 0$$

The coefficient ξ is called the “imitation rate”. The number of workers per product L_t /Q_t converges asymptotically to a constant $l \equiv L_t /Q_t$.[6] Each sector requires $K_{it} = A_{it}x_{it}$ units of capital, and capital-market equilibrium requires equality between supply and demand of capital:

$$K_t = \int_0^{Q_t} K_{it} di = \int_0^{Q_t} A_{it} x_{it} di$$

Profit maximizing action implies that all sectors produce the same amount of output, *i.e.* $x_{it} = x_t$, for all *i*, so

$$K_t = \int_0^{Q_t} K_{it} di = \int_0^{Q_t} A_{it} x_{it} di = x_t \int_0^{Q_t} A_{it} di = x_t Q_t A_t$$

where A_t is the average productivity parameter:

$$A_t \equiv \frac{1}{Q_t} \int_0^{Q_t} A_{it} di$$

Define the capital stock per efficiency unit of labour as $k_t \equiv K_t /(A_t L_t)$. The common amount of output of each sector can now be calculated as

$$x_{it} = x_t = \frac{K_t}{A_t Q_t} = k_t l$$

This implies that the aggregate production function becomes

$$Y_t = Q_t^{\alpha-1} \left[\int_0^{Q_t} A_{it} x_{it}^{\alpha} di \right] L_t^{1-\alpha} = A_t L_t f(k_t)$$

where

$$f(k_t) = k_t^{\alpha} .$$

---

[6] If $dQ_t /dt = \xi L_t$ and $dL_t /dt = g_L L_t$, where g_L is the rate of growth of the number of workers, then $dQ_t /Q_t = dL_t /L_t$ implies that $\xi l = g_L$.

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