The Role of R&D and Patent Activity in Economic Growth: Some Empirical Evidence

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Abstract

This paper explains growth of labour productivity through (inter)national spillovers from R&D and patenting. We develop a formal model that is tested for Germany, France, the United Kingdom and the United States of America using a new set of panel data. The results indicate that, for the period 1957 until 1991, domestic R&D has an indirect and positive impact on productivity growth for the economy as a whole via technological catch up. For the period 1974–1991 we only find such a postive effect for French manufacturing.

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JEL-classification: O11, O31, O41

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1 Introduction

The aim of this paper is to explain differences in growth rates of labour productivity across countries and over time through changes in technological knowledge. Both formal theorists and empirical scholars have always been interested in economic growth differences, as these affect the standards of living. On the empirical side, economic historians like David (1991), Mokyr (1990) and Abramovitz (1991) are convinced of the crucial role technology has played since the First Industrial Revolution started around the turn of the 18th century, the beginning of the period of "modern" growth. In their opinion, technological progress is path-dependent, as it is a learning and feedback mechanism, dependent on the specific characteristics of the economy (Abramovitz, 1991). Furthermore, diffusion of knowledge takes place only gradually (Salter, 1966) and varies across countries and over time (Gerschenkron, 1962). A second group of empirical scholars are the growth accountants like Denison (1967) and Maddison (1995a), who try to calculate with a Solovian type growth model the contribution of various economic forces, among which capital accumulation, on productivity growth. The residual in this model, the so called Abramovitz Residual or Total Factor Productivity, is sometimes labeled as "technical change" (Solow, 1957). The growth accounts thus deal with technology as a purely exogenous variable. Moreover, "... accounting by itself cannot generate causal inferences" (Aghion and Howitt, 1998, p.416). Therefore a part of the productivity growth differences cannot be explained within this framework, and the residual remains a "measure of our ignorance" (Abramovitz, 1991).

In contrast, modern endogenous growth models attempt to endogenize technology. They explain growth differences through 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.

The value added of the current paper lies in the explicit application and estimation of an endogenous growth model and the use of a data set in which the time series of the variables are internationally comparable. This paper 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 (Section 3). It describes the main assumptions of the benchmark model of growth and trade in which technology drives growth. The model will be used as a starting point for the empirical part of this paper. 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

Nothwithstanding the encouraging development in formal theory, the empirical basis of these new growth models is still very thin. Various scholars already tried to estimate the contribution of R&D to productivity, either in levels or in growth rates. These studies use different methodologies and data, so that the outcomes are varying and comparison is difficult. We will concentrate on the results and especially on international spillovers between industrialized countries.

The subject of international spillovers is interesting as it lies in the nature of knowledge to diffuse across national borders (Keely and Quah, 1998, p.24). Intranational spillovers (*i.e.* inter- and intraindustry spillovers within an economy) have been scrutinized more often by micro- or meso-level studies like those of 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. Then the idea of geographical localization came to the forefront again, and applied in, for instance, Jaffe et al. (1993). However, evidence for international spillovers remained relatively weak compared to that of intranational spillovers. Some scholars even calculated that intranational spillovers exceed international spillovers significantly. One of them is Branstetter (1996), who used microlevel data in order to estimate intranational spillovers. He considered this as the proof for endogenous growth theory, as multiple equilibria arise and growth differences then persist. In another study, Lichtenberg (1992) found that there are no complete, or no instantaneous international R&D spillovers.

Nevertheless, despite the mixed results, the evidence tends to confirm the existence of international spillovers. Many studies estimated that the contribution of foreign R&D to domestic productivity is large. In a highly influential article, Coe and Helpman (1995) found that, in a sample of 22 countries, both domestic and foreign R&D contribute significantly to TFP. Moreover, foreign R&D is becoming more important over time, especially for smaller countries. Finally, Coe and Helpman found that about one quarter of the returns from R&D in the seven largest countries are accrued to their trading partners. Criticism on these results came from among others Keller (1997a). He found that the composition of imports played no particular role in estimating positive and large spillovers, although he argued this did not imply that diffusion of embodied technology is not trade-related. In another paper, Keller (1997b) modelled general spillovers versus trade-related spillovers from R&D and calculated that international trade contributed 20 per cent of the total impact on productivity from foreign R&D. He also found that the contribution of foreign R&D varied across countries, and that a country's own R&D was more important than that of the average foreign economy. Finally, Keller had tried to disentangle embodied and disembodied technology, but this appeared to be difficult. Technology can be embodied in traded goods and intermediates, but can also flow disembodied via investments, or via international communication networks. In his opinion, alternative channels should be included, such as Foreign Direct Investment (FDI).

Lichtenberg and Van Pottelsberghe (1996) included FDI flows, both inward and outward. The latter is considered as a proxy for technology sourcing, which is often done by multinationals. Using a new weighting scheme for foreign R&D and a part of the sample of Coe and Helpman (1995), Lichtenberg and Van Pottelsberghe (1996) found that domestic R&D is important (especially for the larger countries), like Coe and Helpman did, although with lower elasticities to output. With respect to foreign R&D, the channels of imports and technology sourcing are playing 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 international technology transfer per se. The rate of returns on foreign R&D via the other two channels are very high. Finally, the impact of technology sourcing is larger for many industrialized countries via the American R&D stock than via imports from the USA.

On the industry-level, Bernstein and Mohnen (1998) scrutinized R&D intensive sectors in the USA and Japan and their effects on each other's production structure and productivity. Over a short period, R&D appears to complement international spillovers, but over a longer period, the results differ between the USA and Japan. The latter's R&D intensity decreases then. Furthermore, American R&D affects the productivity growth of Japanese industries more strongly (60 per cent of the growth is attributable to the American influence) than the other way around (20 per cent in particular). Finally, social rates of return appear to be high again (3,5 to 4 times greater than the private return, which amounts about 17 per cent in both countries). However, this is not out of line as can be seen from Nadiri's (1993) overview of empirical studies on rates of return to R&D.

Park (1995) distinguished government and private R&D like Lichtenberg (1992), but used a panel data set instead of cross-country data. Furthermore, Park calculated the amounts of two kinds of spillovers, namely into production and into research. Foreign R&D appeared to spill over via the domestic production function to productivity growth, whether the USA is included into the sample (of 10 OECD countries over the period 1970–1991) or not. However, the effect of foreign R&D on domestic R&D is only observable 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) found 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 it indirectly via domestic private R&D, as public R&D is often basic research and does not have direct impact on growth rates.

Nadiri and Kim (1996) analyzed the effect of R&D spillovers on TFP growth in the seven largest economies (G7) in the period 1965–1991. They criticized Coe and Helpman (1995) and Park (1995) in that they were not able to distinguish the productivity effect of R&D spillovers from the factor bias effect. Furthermore, they accounted for country-specific effects. The results indicate that benefits from spillovers differ across countries, where the domestic R&D is relatively important for the USA. The spillovers from American research on one another's productivity growth are sizeable, while reversely only Canada and Japan have some influence on American economic growth. 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 did not focus on R&D, but on (international) patenting activity as a measure of knowledge accumulation and diffusion. Keely and Quah (1998) argued that intellectual property rights matter 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 of patents with productivity and R&D 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 an input 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" (p.252). They use a cross-section of 19 OECD countries, with patent applications by reporting country and country of residence of the inventor in 1988, and estimate a simultaneaous equations model. They found that productivity levels rather than growth rates explain a country's ability to adopt or innovate. Furthermore, international diffusion rates are about half of the domestic ones on average. They also estimate that the contribution of the USA to productivity growth worldwide is sizeable, followed by Japan and Germany. The latter affects European economies more whereas Japan's influence is observable elsewhere. Nothwithstanding the high rates of diffusion, barriers (*e.g.*, in the institutional area) are still large enough to let productivity differences to persist. Finally, it appears that human capital (in the form of education and research scientists and engineers) is crucial for the ability to adopt, next 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, Eaton and Kortum (1997) also include research (in particular, research employment) into a growth model next to patenting activity in order to explain productivity differences. This is a new step forward as the above discussed studies did 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). However, Eaton and Kortum (1997) used a cross-section data set and no panel data.

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 applied an endogenous growth model using patent data. However, they did not consider international diffusion. We have to develop and test models that are capable of explaining processes of growth and international spillovers.

3 Model

In this section, we formulate a multi-country, multi-sector model with international technology spillovers and catch-up in the spirit of work by Aghion and Howitt (1998). The empirical studies discussed in Section 2 give a handle on important research subjects. First, international spillovers are not complete and growth differences will persist (Keely and Quah, 1998, p.26). But both international and intranational spillovers play a role, and will occur via different channels such as trade and FDI. The distinction between disembodied and embodied technology is not made in the current paper, but this distinction would be interesting in future research.

Second, both patenting activity as a proxy for knowledge flows and R&D expenditures should be incorporated into an empirical growth model. Cameron (1996) argued that the Aghion and Howitt model needs to be extended with knowledge spillovers from other countries next to domestic R&D. 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 in a positive way. A country needs a certain knowledge basis 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 art enables a country to catch up with the "technological leader". This is in our case the USA. Moreover, in the discussed studies, the research in the USA appeared to affect other economies' productivity growth significantly, but not evenly across countries. We thus also account for country-specific effects.

Third, we also looked for differences in the effect of R&D expenditures and patenting activity on labour productivity growth between the aggregate economy and manufacturing, as a more disaggregated analysis can provide valuable insights in the process of research and diffusion. Finally, we agree with Crafts' (1997) remark that 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..." (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 built a new data set for the USA, UK, France and Germany, and present the resulting time series in Section 4.

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 be able 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 will briefly discuss the underlying theoretical structure of the model and discuss technological progress and the role of spillovers in some more detail.

Basically the model is a multi-country model. In each country we have three sectors:[1]

1. an R&D-sector producing blueprints (or patents A) for new products i using primary resources and previous accumulated knowledge, home and abroad;

2. an intermediate-goods sector monopolized by the holder of a patent to the latest generation of differentiated product x_{it} using capital K_{it}, according to production function

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

where A_{it} is the productivity parameter of latest version of intermediate product i. Here we assume that successive vintages of the intermediate product are produced by increasingly capital intensive techniques. Profit maximizing implies that all sectors supply a common amount of output, as is shown, for instance, in 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:

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

where Q_t is the number of differentiated products. Brands x_i substitute well for each other: the elasticity of substitution between every pair of available brands ε equals $1/(1-\alpha) > 1$.

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. Immitation of ‘old’ products increases the number of differentiated products Q_t (horizontal innovations) but does not add to the social knowledge pool. In short: innovation generates growth and immitation spreads the research input over more sectors. Consumers maximize utility, which they derive from a set of differentiated products, over an infinite horizon given their budget constraint.

[1] 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.

To avoid the scale effect of R&D, 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 immitation is a serendipitous process. This means that imitation just happens: no one spends resources attempting to immitate. The flow of immitation products can now be written as:

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

which asymptotically converges to a constant $l \equiv L_t/Q_t$.[2] The coefficient ξ is called the "immitation rate". 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 implies that all sectors produce the same amount of output, *i.e.* $x_{it} = x_t, \forall i$, so

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

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 $k_t \equiv K_t/(A_tL_t)$. The common amount of output of each sector can now be calculated as

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

This implies that the aggregate production function becomes

$$\begin{aligned} Y_t &= Q_t^{\alpha-1}\left[\int_0^{Q_t} A_{it}x_{it}^{\alpha}di\right]L_t^{1-\alpha} \\ &= A_tL_tf(k_t) \end{aligned}$$

where

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

[2] 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 $\xi l = g_L$.

Summarizing, there is a stock of capital K_t embodied in machines. New capital is produced at rate I_t. Capital, consumption and research are produced by labour L_t and intermediate goods x_{it}:

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

where k_t is defined as the capital stock per efficiency unit of labour $(K_t/(A_t L_t))$ and Q_t is the number of intermediate goods that have been created by an immitator. The flow intermediate products is such that the ratio of Q over L is constant. Capital-market equilibrium and the production function of final output produces 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

$$g_t = g_{A,t} + \alpha \frac{dk_t/dt}{k_t} \tag{1}$$

3.1 Output per efficiency unit

The second term on the right-hand side 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, this can be written as:

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

where $i_t \equiv I_t/K_t$, and I_t is gross investment.

3.2 Technological progress

Define $\hat{A}_t$ as the "leading-edge technology parameter", that is the technology used by the "technological leader". Assume that the ratio of the leading-edge technology and the average technology of a follower-country $\Omega_t \equiv \hat{A}_t/A_t$ converges to a constant, say $1 + \sigma$. This implies that in the long run:

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

Furthermore only innovations add to the stock of knowledge and innovations replace an existing technology with the leading-edge technology. The flow of innovations depends on the arrival rate of innovations ϕ_t and the change of technology $\hat{A}_t - A_t$:

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

or

$$g_{A,t} = \frac{dA_t/dt}{A_t} = \phi_t\,(\Omega_t - 1) \tag{3}$$

The leading-edge technology grows at rate

$$\frac{d\hat{A}_t/dt}{\hat{A}_t} = \sigma\phi_t$$

where again ϕ is the arrival rate of innovations and σ is the impact of innovations, or the "size parameter".[3]

3.3 Spillovers

Sofar the model can be thought of being applicable to all countries j considered. Now, we introduce phenomena like convergence, international spillovers, and technological leadership in the model. More specifically, we do so by focusing on the rate of technology progress, $g_A^i \equiv \Delta \ln A^i$. Above it was assumed that the flow of innovations depends on the arrival rate of innovations ϕ_t and the change of technology $\hat{A}_t - A_t$, now 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.

Define the 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 $\sum_j \omega^j = 1$. Suppose that country k is the technological leader,

[3] Note that:

$$\begin{aligned}
\frac{d\Omega_t/dt}{\Omega_t} &= \frac{d\hat{A}_t/dt}{\hat{A}_t} - \frac{dA_t/dt}{A_t} \\
&= \sigma\phi_t - \phi_t\left(\frac{\hat{A}_t - A_t}{A_t}\right) \\
&= \sigma\phi_t - \phi_t\,(\Omega_t - 1)
\end{aligned}$$

So

$$g_A = g_{\hat{A}} = \sigma\phi_t = g_\Omega + \phi_t(\Omega - 1)$$

and in the long run when $g_\Omega = 0$, $\Omega = 1 + \sigma$.

then $\omega^k = 1$, so $\ln \hat{A}_t = \ln A_t^k$. It is assumed that, in the long run, $\hat{A}_t / A_t^j$ converges to a constant, that is[4]

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

This implies that, in the long run, $g_A = g_{\hat{A}}$. Now suppose that the change in the level of technology in country j depends on the technological gap with the leader:

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

where the term between brackets on the right-hand side is the gap. The last term is the rate of growth of the technology of the leader country. In the long-run the gap is closed, which implies that we expect β to be equal to 1.

Parameter λ_t measures convergence. We allow the speed of convergence to be influenced by own R&D:

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

where n_t^j is the reciprocal of R&D productivity, measured as R&D-expenses over GDP. The idea is that in order to adapt foreign technology, 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. The term λ_t is assumed to be positive. If a country j's technology is below average, then a positive value for λ_t signals convergence to the average. Other factors that may attribute to the process of adjustment are simply captured by the constant term λ. One can think of organisational and managerial factors and knowledge not embodied in own R&D and in patents.[5]

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:

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

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.

[4]Note that $0 < A_t^j / \hat{A}_t < 1$, so that $z^j < 0$.

[5]Here we take λ to be constant across countries, so λ_t differs across countries only because the ratio of R&D expenditure over GDP differs. However, it may be reasonable to assume that that are managerial differences and differences in educational and financial institutions between countries. For the set of countries and the time period we are considering here, these differences are small if perhaps not negligible.

3.4 The system

In the next sections we describe the construction of the data and we discuss the estimation resultsfore presenting the data and the estimation results. But first we summarize the model.

Summarizing, the model consists of the following equations:

$$g_t^j = g_{A,t}^j + \alpha g_{k,t}^j \tag{6}$$

$$g_{A,t}^j = -\lambda_t \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j \right) + \beta g_{\hat{A},t} \tag{7}$$

$$\lambda_t = \lambda + \gamma g_{n,t}^j \tag{8}$$

$$g_{n,t}^j = g_{D,t}^j - g_{Y,t}^j \tag{9}$$

$$g_{k,t}^j = i_t^j - \left(\delta^j + g_{A,t}^j + g_{L,t}^j \right) \tag{10}$$

$$g_{Y,t}^j = g_t^j + g_{L,t}^j \tag{11}$$

The symbols have the following meaning:

A_t^j	the level of techology of country j
$\hat{A}_t$	the level of techology 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
$g_{\hat{A},t}$	growth rate of leading-edge technology at time t, here the USA
λ_t	speed of convergence of technology 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-linearized 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:

$$g_t^j = g_{A,t}^j + \alpha g_{k,t}^j$$

$$
\begin{aligned}
&= g^j_{A,t} + \alpha \left[i^j_t - \left(\delta^j + g^j_{A,t} + g^j_{L,t} \right) \right] \\
&= (1-\alpha) g^j_{A,t} + \alpha \left(i^j_t - \delta^j - g^j_{L,t} \right) && (12)
\end{aligned}
$$

$$
\begin{aligned}
g^j_{A,t} &= -\left(\lambda + \gamma g^j_{n,t} \right) \left(\ln A^j_{t-1} - \ln \hat{A}_{t-1} - z^j \right) + \beta g_{\hat{A},t} \\
&= -\left[\lambda + \gamma \left(g^j_{D,t} - g^j_t - g^j_{L,t} \right) \right] \left(\ln A^j_{t-1} - \ln \hat{A}_{t-1} - z^j \right) \\
&\quad + \beta g_{\hat{A},t} && (13)
\end{aligned}
$$

Equations (12) and (13) will be estimated, but first we take a look at the data.

4 Data

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

In the current section, we show the development of the economic variables in equations (12) and (13) for the USA, UK, France and Germany in the period after the Second World War. Total economy and manufacturing are compared as “sectors”, as far as the data allow us to do so. Appendix A presents the original time series on the variables and their sources. We constructed proxies for the economic variables in order to estimate the effects of technological change on labour productivity growth (Section 5). Appendix A shows a list of the empirical counterparts of these variables.

Figure 1(a) 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 French growth rate of labour productivity had always been positive in this period, whereas the other three countries experienced some repercussions (Figure 1(b)). German labour productivity had also been increased fast, but it did not succeed yet in catching up with the USA in 1991. The Anglo-American gap remained relatively constant during the period under consideration. In manufacturing, labour productivity levels rose faster than in total economy (Figures 2(a) and 2(b)). Here, France did not catch up with the American labour productivity level, as the USA were developing as fast as France. Again, the UK lagged behind, with the gap to the USA even widening, as Figure 2(a) shows. Comparing Figures 1(b) and 2(b), we observe that in general, labour productivity growth in manufacturing was higher than in the

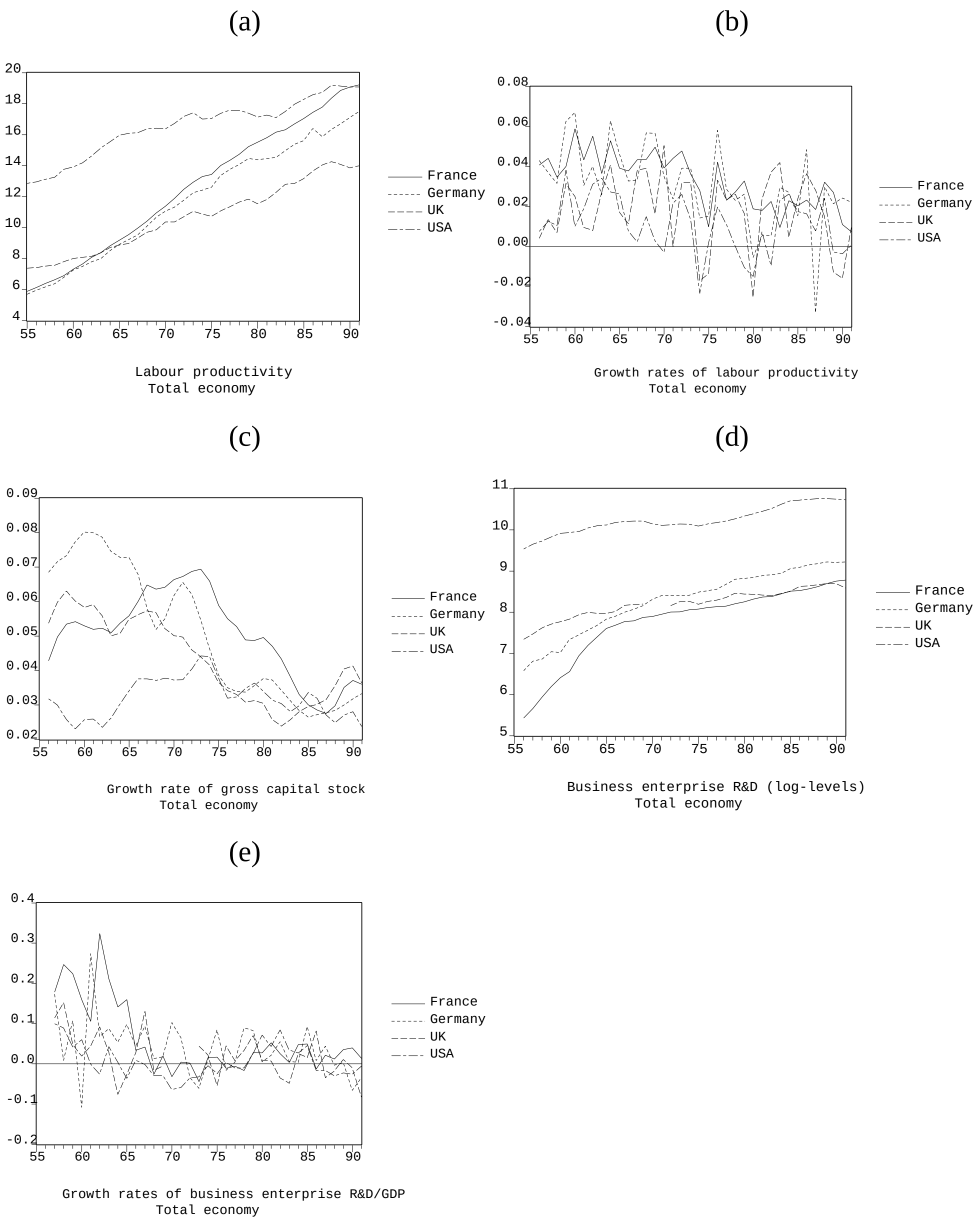


Figure 1 *Total economy, 1955–1991*

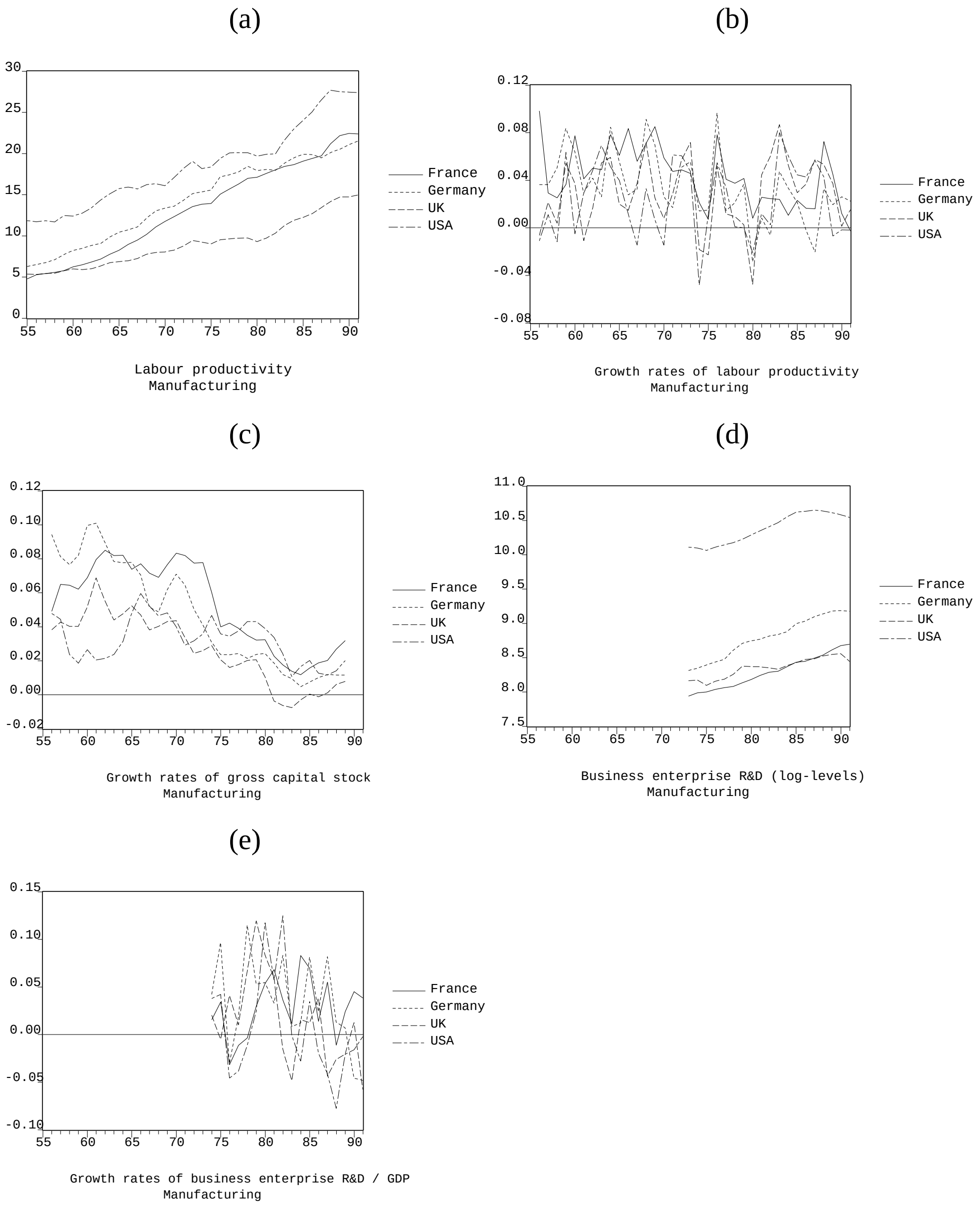


Figure 2 *Manufacturing, 1955–1991*

total economy, but fluctuating more strongly. Manufacturing industries are sensitive to the business cycle, which find expression in the growth rates of labour productivity. In total economy, other sectors like the service sector may meet a change in labour productivity growth in manufacturing, at least partially.

Traditionally, physical capital accumulation had 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 the share of capital accumulation in the growth of labour productivity. For both total economy and manufacturing, Figures 1(c) and 2(c) display the growth in gross capital stocks. The growth patterns are rather similar, although the growth rates declined faster in manufacturing. From these pictures, we can hardly draw unambiguous conclusions on the connection between capital accumulation and labour productivity growth. Only the growth rate differences between the countries are clear. Up to the early seventies, Germany experienced high growth rates, whereas in the subsequent decade, French rates were larger. The British capital stock grew less rapidly, but in all three economies the growth rates declined over time. The American growth rates are on the average low, especially in total economy before 1975, but the level of its capital stock is relatively higher. Furthermore, the growth rates suggest that they go up and down with the business cycles, like the labour productivity growth rates.

According to endogenous growth theories, of which one is discussed in Section 2, technological development affects the national growth rates of labour productivity, and thus also differences between countries. Capital accumulation then plays 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 1(d) shows the change in (log-)levels of R&D-expenditures from 1956 to 1991 in total economy, whereas Figure 2(d) shows us the development in manufacturing. Unfortunately, no consistent time series on manufacturing R&D-expenditures before 1973 are available. Comparing total economy with manufacturing in the period 1973–1991, we see that manufacturing R&D accounts for a large part of total business enterprise R&D. The growth patterns differ slightly between both “sectors”. Figures 1(e) and 2(e) display the growth rates of R&D net of the growth rate of GDP (or value added). In total economy, French growth rates of R&D were high before 1965, with Germany a good second. Figures 1(d) and 2(d) show that the American-British R&D ratio remained constant, while Germany and France caught up in some extent. In total economy, especially French R&D intensity 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. The USA was the first Western country to start with systematic formal R&D, in the 1950s. Furthermore, the pattern of growth in R&D seems to be sensitive to the business cycle.

In Figure 3(a), the yearly numbers of applications 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 patent is that they contain technological knowledge. Particularly, patents are the outcome of innovation processes, whether or not started 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 more often sensitive to bureaucratic procedures at the patent offices. Applications are no patents yet (*i.e.* grants), but they reflect the extent 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 the other countries in some way, either 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. Then 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 3(a) 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, less or more, uniform market, where one may expect certain profits from the patent. 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. As in the current paper, the USA are considered as a "technological leader". The innovative effort of American firms and individuals is significant, although the share of foreigners had been increased during the period. The Anglo-American gap is very large, but France and Germany do not perform much "better". The gaps with the USA had even widened between 1940 and 1991.

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 take time to come into use as the knowledge 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 3(b) displays the resulting 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 between 1975 and 1980. The French growth rates are fluctuating more strongly, whereas the American rates are on average lower.

5 Estimation results

In Section 3 the model is presented and the equations are derived. Below we present the equations that are estimated. The first equation is the log-linearized Cobb-Douglas production function (compare equation (12) above), where we added lagged productivity growth because of severe autocorrelation. Furthermore, we lagged the investment term for statistical reasons. This may be explained by a "time-to-build" argument: It takes some time for investment to become productive. The second equation, which is the same as equation (13) above, describes the development of technological progress, which depends on the technological gap with the leader.

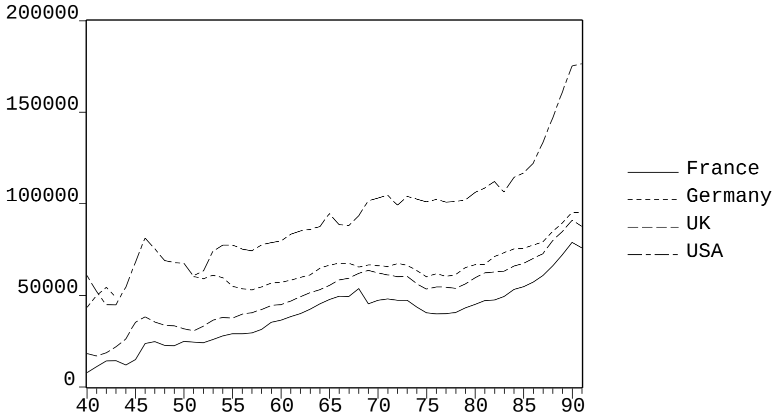
$$\begin{aligned} g_t^j &= (1-\alpha-\rho) g_{A,t}^j + \alpha \left(i_{t-1}^j - \delta_{t-1}^j - g_{L,t-1}^j \right) + \rho g_{t-1}^j \\ g_{A,t}^j &= -\left[\lambda + \gamma \left(g_{D,t}^j - g_t^j - g_{L,t}^j \right) \right] \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j \right) + \beta g_{\hat{A},t} \end{aligned}$$

The equations are estimated using (iterative) least squares on a panel of annual observations for both total economy and manufacturing. The countries considered are France, Germany, the United Kingdom and the United States of America. The time period considered is 1957–1991. In some cases the time period is shorter because of lack of data, especially for manufacturing. The interesting parameters are the capital share in output α and the autocorrelation coefficient ρ, and the parameters in the technical progress function: λ, γ, β, and z.

Table 1 shows the estimation results of the production function for both total economy and manufacturing in the period 1955 to 1991 and 1974 to 1991. We present two 'periods' in Table 1 because for manufacturing, it is namely only possible to estimate the technology function for period 1974 to 1991.

From the estimation results presented in Tables 1 to 4 we can draw the following conclusions. First, the fit is not particularly good for the productivity equations. Nevertheless, the long-run capital share is 0.32 (0.08/(1-0.75)) for total economy for

(a)



Yearly numbers of applications

(b)

10 year-moving sum of number of applications (growth rates)

Figure 3 *Applications, 1940–1991*

Table 1 *Productivity: total economy and manufacturing (t-values between brackets)*

	Total economy		Manufacturing	
	1955-91	1974-91	1955-91	1974-91
α	0.08	0.08	0.57	0.58
	(2.95)	(2.26)	(11.23)	(7.89)
ρ	0.75	0.80	0.18	0.15
	(13.75)	(11.19)	(2.97)	(1.64)
Observations	136	72	132	68
Adj R^2:				
FRA	0.15	-	0.43	-
GER	-[a]	-	0.47	0.32
UK	-	-	0.35	0.29
US	0.01	-	0.28	0.27
Durbin-Watson:				
FRA	2.199	2.232	1.918	1.849
GER	3.019	3.212	2.688	2.911
UK	2.438	1.974	1.853	1.599
US	2.443	2.375	1.437	0.959

[a]: negative

Table 2 *Technology: total economy, 1957–1991 (t-values between brackets)*

	1a	1b	2a	2b	3
λ	0.04		0.04		
	(1.79)		(1.79)		
λ_{FRA}					−0.01
					(−0.31)
λ_{GER}					0.03
					(1.04)
λ_{UK}					0.12
					(2.44)
γ	0.25	0.33			
	(2.22)	(1.42)			
γ_{FRA}			0.27	−0.43	−0.42
			(1.50)	(−1.07)	(−1.04)
γ_{GER}			0.21	0.63	0.23
			(1.26)	(2.05)	(1.34)
γ_{UK}			0.24	0.76	−0.09
			(0.87)	(1.24)	(−0.20)
β	0.83	0.85	0.84	0.85	0.83
	(10.56)	(14.40)	(9.86)	(14.62)	(10.00)
z_{FRA}	−0.64	−0.51	−0.65	−1.25	−1.25
	(−6.37)	(−1.64)	(−5.67)	(−4.11)	(−4.02)
z_{GER}	−0.48	−0.52	−0.49	−0.43	−0.50
	(−8.27)	(−3.46)	(−7.30)	(−7.06)	(−5.50)
z_{UK}	−0.45	−0.39	−0.45	−0.52	−0.52
	(−5.27)	(−1.88)	(−4.63)	(−5.24)	(−18.61)
Observations	98	98	98	98	98
Adj R^2:					
FRA	0.45	0.48	0.45	0.53	0.51
GER	0.47	0.43	0.47	0.45	0.48
UK	0.48	0.40	0.48	0.41	0.52
Durbin-Watson:					
FRA	0.321	0.473	0.325	0.717	0.693
GER	0.391	0.437	0.384	0.476	0.396
UK	0.193	0.236	0.191	0.231	0.166

Table 3 *Technology: total economy, 1974–1991 (t-values between brackets)*

	1a	1b	2a	2b	3
λ	0.17		0.19		
	(4.88)		(5.37)		
λ_{FRA}					0.23
					(3.34)
λ_{GER}					0.17
					(2.65)
λ_{UK}					0.17
					(3.38)
γ	0.21	2.07			
	(0.27)	(1.86)			
γ_{FRA}			−7.89	−1.22	−9.34
			(−2.77)	(−0.30)	(−2.54)
γ_{GER}			−0.70	2.55	−0.75
			(−0.77)	(1.65)	(−0.77)
γ_{UK}			1.64	2.03	1.46
			(1.43)	(1.22)	(1.32)
β	0.88	0.78	0.89	0.77	0.91
	(12.49)	(12.51)	(13.75)	(12.48)	(14.00)
z_{FRA}	−0.83	−0.74	−0.87	−1.01	−0.85
	(−37.40)	(−7.72)	(−40.64)	(−1.75)	(−43.43)
z_{GER}	−0.48	−0.46	−0.49	−0.46	−0.49
	(−32.12)	(−20.18)	(−31.63)	(−24.68)	(−24.08)
z_{UK}	−0.59	−0.58	−0.58	−0.58	−0.58
	(−41.06)	(−20.49)	(−51.75)	(−19.23)	(−42.10)
Observations	54	54	54	54	54
Adj R^2:					
FRA	0.65	0.53	0.77	0.55	0.78
GER	0.71	0.63	0.71	0.63	0.71
UK	0.81	0.71	0.83	0.70	0.83
Durbin-Watson:					
FRA	0.346	0.256	0.514	0.199	0.580
GER	0.475	0.565	0.481	0.677	0.492
UK	0.484	0.395	0.663	0.389	0.645

Table 4 *Technology: manufacturing, 1974–1991 (t-values between brackets)*

	1a	1b	2a	2b	3
λ	0.17		0.13		
	(4.41)		(3.62)		
λ_{FRA}					0.15
					(1.87)
λ_{GER}					0.20
					(2.72)
λ_{UK}					0.09
					(1.87)
γ	−0.02	2.84			
	(−0.02)	(2.97)			
γ_{FRA}			−3.27	−0.31	−3.70
			(−2.08)	(−0.13)	(−1.52)
γ_{GER}			−0.41	2.23	−0.72
			(−0.66)	(1.83)	(−0.79)
γ_{UK}			3.45	5.76	4.21
			(1.97)	(3.51)	(2.29)
β	0.89	0.79	0.90	0.80	0.88
	(12.13)	(14.57)	(16.34)	(15.56)	(16.57)
z_{FRA}	−0.83	−0.79	−0.89	−1.27	−0.88
	(−36.62)	(−19.04)	(−21.00)	(−0.37)	(−16.80)
z_{GER}	−0.49	−0.46	−0.51	−0.46	−0.49
	(−30.01)	(−32.36)	(−21.57)	(−24.38)	(−28.82)
z_{UK}	−0.59	−0.60	−0.58	−0.59	−0.59
	(−39.65)	(−33.94)	(−65.33)	(−75.71)	(−70.08)
Observations	54	54	54	54	54
Adj R^2:					
FRA	0.66	0.51	0.71	0.55	0.70
GER	0.71	0.63	0.70	0.63	0.72
UK	0.81	0.82	0.86	0.85	0.87
Durbin-Watson:					
FRA	0.351	0.332	0.703	0.255	0.687
GER	0.457	0.866	0.457	0.709	0.507
UK	0.501	0.795	0.836	1.403	1.069

the whole period and 0.40 for the period 1974 to 1991, which is not unreasonable. In previous empirical studies, such as Mankiw, Romer and Weil (1992), a share of about 33 per cent is considered as the long run share of capital. However, the share of capital in manufacturing is about 0.68, a very high value. The fit for the technology equation is somewhat better for manufacturing compared to total economy. Second, not all parameters are significant at a 5% significance level. More importantly, some parameters do not have the expected signs.

More interesting are the estimations for the technology function. First, we discuss the results for the total economy, for the periods 1955 to 1991 and 1974 to 1991. Here, we present three estimation versions. One is with a common parameter for γ, measuring the impact of R&D on technological catch-up, for all countries considered (column 1 in Table λ, measuring all other changes in knowledge not captured by formal R&D activity. The second version is one equation in which γ is allowed to differ between countries, whereas in the third version λ has also cross section specific values.

In total economy over the whole period, own R&D significantly affects the speed at which countries adapt foreign technology, if we take a common parameter for R&D. Leaving out the parameter λ does not improve the results. When allowing for country-specific coefficients for the R&D parameter, the fit is less good. Only for Germany, when leaving out the λ parameter, own R&D seems to have some effect on the reduction of the technology gap with the USA (γ equals 0.63). In the period after 1974, this is valid for France (with γ equal to -7.89 in the third column of table 3 and -9.34 in the fifth column). However, the sign is negative, which is not what we expected.

Other factors, captured by the constant term λ, that may influence the adjustment process (see Section 3) seem to play a significant and positive role in the total economy only in the period 1974 to 1991. The negative effects of R&D in France are partly compensated by these other factors.

For manufacturing there are some differences. As can be seen from Table 4, the parameter γ, whether or not allowed to differ across countries, is only significantly different from zero with a positive influence if λ is excluded from the regressions. However, if the parameter is country-specific, it is only significant for the UK. If λ is included in the equation, the French γ is again negative. In any case, λ plays a role, although less superior than in total economy.

In terms of our model we can conclude that technological divergence takes place in France, while technological catch up is occurring in British manufacturing. R&D

can contribute positively to technological catch up in the UK and Germany if we do not allow for other factors, *i.e.* $\gamma = 0$.

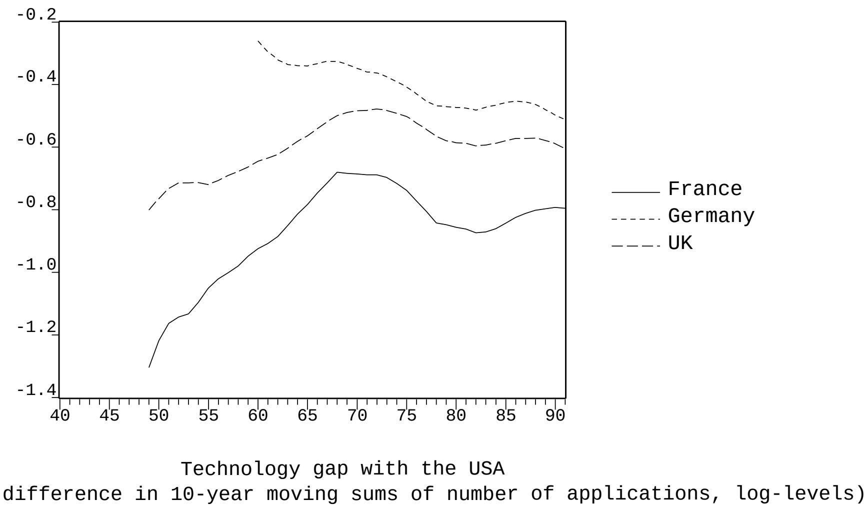


Figure 4 *Technology gap vs. US, 1949–1991*

The other parameter estimates are more consistent. For both total economy and manufacturing parameter β does not differ significantly from 1 as was expected. Parameters z indicate the long-run technology level with respect to the US. In the theoretical model these relative technology levels were supposed to be constant in the long run. From the estimation result in table 2 in column 1a, we can conclude that, in the long run in total economy, France has a level of technology of about 53% (calculated as $\exp(-0.64)$) of that in the US. For Germany and the UK these numbers are 62% and 64%, respectively. In the shorter period from 1974 onwards, these numbers are about 44%, 61% and 55%, respectively (see columns 1a in Table 3 and Table 4). These estimation results more or less are comfirmed with the data as can be seen from Figure 4. 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 US.

6 Conclusions

In this paper we try to explain growth differentials across countries by technological developments. It builds on recent endogenous growth models, which combine imperfect competition with innovations-based growth and learning-by-doing in innovation. These forces generate spillovers from industrial research and patenting activity. Our model is a multi-country, multi-sector model 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 and manufacturing in the period 1956–1991.

From the estimation results, which undoubtedly can be improved, 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 R&D expenditures have an indirect and positive effect via the adjustment of the gap with the USA. Domestic efforts to gain knowledge thus are important 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 differ between the latter three, so the technological gaps also differ, and herewith the growth rates of productivity. 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 some earlier estimations not included in this paper) that the results also differ between time periods, such as 1956–1973 and 1973–1991. Also the results differ if we compare the estimation results for the economy as a whole and manufacturing. The major reason for these differences is the difference in the estimation periods.

Despite our favourable results, one has to bear in mind that 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. Human capital accumulation has only been accounted for in the model implicitly.

To conclude, the results vary across countries, sectors and over time. This is confirmed by other empirical studies (as discussed in Section 2). Crafts (1997, p.64) argued that "... success in "technology transfer" varied and seems to have been affected by institutional and policy differences...". 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. The challenge lies in introducing these entities—which are not easy to measure—in formal models of economic growth.

A Data[6]

We have constructed proxies for both the total economy and manufacturing (the latter as far as available) on the economic variables in equations (12) and (13). The original data used for construction of these proxies are discussed below, whereas the resulting time series are listed in Tables A.2–A.8. Note that total (gross) investment and capital are the sum of non-residential structures and machinery and equipment. Furthermore, the depreciation rate δ_t^j 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. We used data on the total numbers of applications in a country, assuming that this reflects international diffusion of knowledge as foreign applications are accounted for. The proxies used in estimation are:

- growth rate of labour productivity $g_t^j = g_{Y,t}^j - g_{L,t}^j$, where
  - $g_{Y,t}^j$ = log-differenced GDP
  - $g_{L,t}^j$ = log-differenced employment
- growth rate of the reciprocal of R&D-productivity $g_{n,t}^j = g_{D,t}^j - g_{Y,t}^j$, where
  - $g_{D,t}^j$ = log-differenced R&D-expenditures
  - $g_{Y,t}^j$ = log-differenced GDP
- growth rate of technology $g_{A,t}^j$ = log-difference of 10-year moving sum of the number of total applications in country j
- growth rate of leading-edge technology $g_{\hat{A},t}$ = log-difference of 10-year moving sum of the number of total applications in the USA
- level of technology $\ln A_{t-1}^j$ = log of 10-year moving sum of number of total applications in country j, lagged one year
- level of technology of leading country $\ln \hat{A}_{t-1}$ = log of 10-year moving sum of number of total applications in the USA, lagged one year

[6]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).

- growth rate of physical capital in efficiency units $g_{k,t}^{j} = i_t^j - (\delta_t^j + g_{L,t}^{j})$, where
  - i_t^j = gross investment I / gross capital stock K
  - $\delta_t^j = (I - \Delta K)/K$
  - $g_{L,t}^{j}$ = log-differenced employment

A.1 Output and employment

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

The time series for both GDP and VA in manufacturing 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 senseful (*e.g.*, GDP and VA are all at factor cost, while the national census series are sometimes at producer or market prices). Using table 3.4, the census series can be rebased 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 or VA to the value at prices of the base year in the original series, both in national currencies. After rebasing, the series are converted into PPP equivalents. For GDP, GDP PPP in 1975 from OECD (1997b, table 3, p. 162) is applied, whereas the manufacturing VA time series are again converted with the manufacturing PPPs as displayed in table 3.3.

In table 3.4 of Van Ark (1996), data are also given for the number of employees for both manufacturing and 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 VA 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 rescaled.

A.2 Capital stocks and investment

Data sources: Kravis et al.(1982), Maddison (1995b), O'Mahony (1996), OECD (1966, 1987, 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 (1995b), tables 7 and 8 on Non-Residential Structures (NRS) and Machinery & Equipment

Table A.1 *1975 PPPs for NRS and ME*

	NRS	ME
UK	0.516	0.539
France	5.341	5.430
Germany	2.404	3.350

(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 rebased 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 (1995b), 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 typed over from table 6.3 (lines 123–144). In Table A.1 the resulting 1975 PPPs are displayed:

O'Mahony (1996) gives data on manufacturing capital stocks (to 1989), but no investment data. However, from the conventional definition $\Delta K = I - \delta K$, we can derive that $i - \delta = I/K - \delta = \Delta K/K = g_K$, so that we can calculate an approach of $g^j_{k,t} = i^j_t - \delta^j_t - g^j_{L,t}$. In Section 4, the growth rates of the capital stocks are compared. It appears that the patterns do not differ too much. The original time series from O'Mahony were in 1985 US $, and were converted back into national currencies with the PPPs in OECD (1987), following the same procedure of calculating PPPs for NRS as above, whereafter the series are rebased and converted into 1975 PPPs, such as the series of Maddison.

A.3 Technology indicators

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

A.3.1 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), whereas those for manufacturing were from the ANBERD database (ISIC-3) of OECD (1995b). Some gaps in the series of Verspagen (1996) were filled with ANBERD data, as these may not differ much from those of Verspagen. Only for the UK in 1970 and 1971 no data were available. The ANBERD data for manufacturing are only available from 1973, whereas the Verspagen data run from 1956 onwards. In general, manufacturing R&D appears to account for the largest part of total R&D expenditures in business enterprise.

Both 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 higer 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 parties only broadly. Unfortunately, R&D indices or PPPs are not available for the present.

A.3.2 Applications. Data sources: Deutsches Patentamt, I.N.P.I., OECD (1991, 1995a, 1997a), WIPO (1983).

The patent numbers are only on aggregated level. Data on manufacturing patent activity must be available, but highly dispersed over national institutes. For the present, we used the aggregated data as a proxy for the technology gap in manufacturing. The sources for data on the total number of applications 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.

Table A.2 *Labour productivity*

	Total economy				Manufacturing			
	USA	UK	France	Germany	USA	UK	France	Germany
1955	12.85	7.38	5.88	5.70	11.83	5.35	4.77	6.28
1956	12.95	7.41	6.13	5.96	11.71	5.31	5.27	6.51
1957	13.11	7.51	6.40	6.18	11.84	5.43	5.42	6.75
1958	13.25	7.57	6.63	6.38	11.70	5.45	5.56	7.10
1959	13.77	7.81	6.90	6.79	12.47	5.76	5.77	7.72
1960	13.91	8.01	7.32	7.26	12.40	5.98	6.23	8.23
1961	14.17	8.08	7.64	7.49	12.77	5.91	6.50	8.47
1962	14.62	8.15	8.08	7.79	13.40	6.01	6.83	8.84
1963	15.13	8.37	8.38	8.00	14.36	6.35	7.17	9.07
1964	15.55	8.72	8.84	8.52	15.11	6.74	7.76	9.87
1965	15.97	8.87	9.19	8.92	15.73	6.87	8.25	10.44
1966	16.09	8.97	9.54	9.22	15.91	6.97	8.97	10.73
1967	16.13	9.32	9.97	9.53	15.68	7.24	9.48	11.09
1968	16.37	9.69	10.41	10.09	16.21	7.78	10.18	12.15
1969	16.42	9.86	10.94	10.67	16.32	7.98	11.08	13.03
1970	16.37	10.37	11.38	11.05	16.09	8.04	11.76	13.37
1971	16.73	10.37	11.89	11.32	17.10	8.27	12.33	13.60
1972	17.17	10.70	12.48	11.78	18.17	8.76	12.94	14.31
1973	17.41	11.05	12.93	12.25	19.05	9.41	13.55	15.13
1974	17.00	10.86	13.30	12.42	18.16	9.24	13.84	15.35
1975	17.04	10.72	13.43	12.61	18.36	9.04	13.93	15.57
1976	17.38	11.08	14.01	13.37	19.40	9.52	15.07	17.15
1977	17.57	11.34	14.34	13.76	20.07	9.63	15.70	17.40
1978	17.57	11.64	14.74	14.08	20.09	9.72	16.30	17.77
1979	17.39	11.84	15.23	14.45	20.08	9.75	16.99	18.44
1980	17.13	11.54	15.52	14.37	19.67	9.29	17.13	17.92
1981	17.26	11.82	15.80	14.45	19.91	9.72	17.57	18.07
1982	17.10	12.27	16.16	14.53	19.96	10.32	18.01	17.96
1983	17.50	12.80	16.32	14.97	21.62	11.26	18.45	18.83
1984	17.96	12.86	16.70	15.38	22.97	11.87	18.64	19.47
1985	18.28	13.17	17.05	15.62	24.01	12.23	19.08	19.90
1986	18.58	13.66	17.45	16.39	25.06	12.68	19.39	19.86
1987	18.73	14.05	17.77	15.86	26.52	13.43	19.71	19.46
1988	19.19	14.26	18.36	16.34	27.68	14.17	21.19	20.11
1989	19.14	14.08	18.86	16.69	27.49	14.71	22.16	20.51
1990	19.07	13.86	19.07	17.10	27.44	14.72	22.43	21.05
1991	19.08	13.99	19.21	17.49	27.39	14.95	22.37	21.53

Table A.3 *Output (mln 1975 PPP$)*

	Total economy, GDP				Manufacturing, value added			
	USA	UK	France	Germany	USA	UK	France	Germany
1955	834084	176990	116607	136129	201134	43392	21030	48794
1956	860143	179012	121354	146332	202942	43177	23014	52735
1957	874773	181422	127724	155050	204077	44138	24315	56332
1958	862934	180950	131698	161866	186272	43574	25157	59343
1959	917072	188300	135993	174399	207464	46194	25711	64957
1960	939418	196519	144248	189916	207877	49941	27883	73639
1961	958130	200401	150585	198550	208334	50024	29320	78050
1962	1009282	202757	159334	207381	226044	50240	31227	81740
1963	1055151	208733	166856	213343	243945	52296	33554	83354
1964	1107824	220035	177871	227386	261149	56425	37019	90748
1965	1171545	225652	185769	239524	283895	58298	39039	97656
1966	1235187	229632	194522	246732	305635	59363	42660	99344
1967	1266626	235125	203902	246748	304806	59762	44857	97122
1968	1318325	242980	212727	261401	320434	63689	47480	107191
1969	1358647	247079	227043	280925	329414	66151	53157	119723
1970	1351816	258649	239599	294626	311066	66550	57925	125799
1971	1379257	254933	251801	302984	316403	66284	61644	127128
1972	1450383	262525	265245	316360	344493	67881	65525	131266
1973	1531393	277540	278711	332604	381340	73405	70091	139651
1974	1521544	273787	288528	333320	363129	72528	72346	138285
1975	1499684	268559	288189	329289	336063	67468	70859	131760
1976	1568485	275222	302245	347163	368653	68817	75859	141846
1977	1640697	282063	311314	357788	395934	70099	78683	144461
1978	1721047	291305	320888	369115	413741	70437	80386	147215
1979	1767754	300596	330910	385289	424163	70308	82327	154520
1980	1752447	292344	337344	389137	401353	64208	81784	151561
1981	1782781	287796	341841	390826	404152	60356	81224	150055
1982	1746556	293325	350593	388238	377976	60484	81933	144793
1983	1808462	302336	353478	394236	401532	62218	82267	146748
1984	1940229	311577	358492	405680	448105	64606	80763	151046
1985	2018897	323137	364844	415065	464066	66330	80448	156264
1986	2087921	335484	374920	425295	478479	67193	80308	158469
1987	2163392	352284	383177	430458	507543	70708	79566	155384
1988	2278211	369577	399244	446975	541363	75683	84311	160289
1989	2324197	377032	415585	463331	538975	79076	88658	165786
1990	2346502	379275	424554	488805	531227	78919	90314	174874
1991	2332107	370692	427859	512147	511880	74657	88606	181401

Table A.4 *Employment (×1000)*

	Total economy				Manufacturing			
	USA	UK	France	Germany	USA	UK	France	Germany
1955	64894	23977	19820	23867	16996	8115	4405	7773
1956	66417	24151	19802	24573	17337	8125	4369	8101
1957	66701	24148	19943	25089	17242	8130	4483	8346
1958	65111	23916	19862	25378	15924	7994	4523	8359
1959	66606	24113	19703	25684	16643	8027	4457	8416
1960	67542	24542	19705	26153	16762	8357	4473	8950
1961	67600	24787	19698	26517	16319	8462	4513	9211
1962	69020	24878	19722	26610	16871	8358	4572	9251
1963	69730	24928	19912	26673	16990	8237	4678	9191
1964	71235	25228	20132	26696	17278	8376	4771	9193
1965	73379	25432	20217	26848	18047	8484	4734	9355
1966	76772	25589	20384	26765	19205	8513	4758	9256
1967	78532	25220	20459	25893	19433	8255	4731	8759
1968	80524	25063	20433	25915	19769	8189	4664	8824
1969	82751	25071	20750	26319	20181	8293	4796	9191
1970	82569	24954	21055	26652	19337	8278	4927	9409
1971	82436	24592	21171	26760	18500	8012	5001	9347
1972	84456	24527	21261	26867	18959	7749	5062	9171
1973	87975	25113	21548	27160	20016	7798	5173	9231
1974	89482	25199	21691	26830	19998	7847	5228	9011
1975	88026	25055	21452	26110	18302	7467	5085	8460
1976	90253	24837	21569	25972	19005	7230	5034	8269
1977	93369	24867	21707	26009	19729	7279	5012	8302
1978	97935	25017	21772	26220	20599	7246	4933	8282
1979	101644	25394	21727	26660	21119	7214	4846	8380
1980	102277	25329	21735	27073	20403	6908	4776	8457
1981	103279	24346	21631	27044	20304	6209	4622	8305
1982	102154	23910	21690	26722	18940	5858	4550	8062
1983	103360	23629	21659	26342	18573	5526	4460	7792
1984	108010	24237	21469	26384	19509	5443	4333	7757
1985	110444	24538	21405	26581	19324	5425	4217	7854
1986	112361	24564	21489	25945	19094	5297	4141	7979
1987	115512	25077	21558	27144	19139	5263	4037	7984
1988	118734	25919	21750	27355	19559	5342	3979	7969
1989	121462	26780	22037	27754	19608	5377	4000	8083
1990	123072	27371	22265	28578	19358	5360	4026	8307
1991	122224	26496	22272	29290	18688	4993	3960	8426

Table A.5 *Gross capital investment (mln 1975 PPP$)*

	Total economy				Manufacturing			
	USA	UK	France	Germany	USA	UK	France	Germany
1955	106764	12904	8912	15762				
1956	116372	14613	10308	18077				
1957	122145	16187	12116	18437				
1958	114568	17573	14272	19824				
1959	126022	18070	16814	22887				
1960	134023	20738	18858	26990				
1961	135694	23541	22505	31178				
1962	145214	23957	25798	35238				
1963	155764	25105	29436	37545				
1964	174457	29188	33855	43234				
1965	203794	32064	36754	46295				
1966	228438	34142	42073	47518				
1967	233740	36736	46158	41770				
1968	254406	39757	49220	44715				
1969	278705	44021	57732	54652				
1970	284601	46866	65512	70890				
1971	297706	51068	73522	79400				
1972	324231	57858	83704	81061				
1973	382544	66707	95580	84294				
1974	428850	79912	111202	84925				
1975	435910	96147	121619	85535				
1976	465314	113502	144499	91657				
1977	540368	126256	155656	97991				
1978	665843	145902	171794	107312				
1979	787579	174322	197612	121738				
1980	858102	196047	232787	134414				
1981	958178	199126	253408	134231				
1982	946778	215090	285098	131509				
1983	929208	230861	297226	136364				
1984	1074562	263501	310238	139770				
1985	1194873	296232	342610	147587				
1986	1185633	313862	375752	158100				
1987	1208232	364355	408194	165143				
1988	1288446	442428	466376	175705				
1989	1389594	524368	514582	192569				
1990	1414540	553936	552988	217758				
1991	1331207	515160	565529	242685				

Table A.6 *Gross capital stock (mln 1975 PPP$)*

	Total economy				Manufacturing			
	USA	UK	France	Germany	USA	UK	France	Germany
1955	1834491	161165	152800	169995	233279	40177	20988	40000
1956	1956144	179723	167459	188046	252767	44133	23186	45399
1957	2101360	196956	186470	206295	275488	47555	26267	50270
1958	2200247	218513	221022	231244	287823	51566	31529	56500
1959	2296672	234377	247319	252337	299087	54213	35621	61915
1960	2379576	250893	268144	281519	310136	57620	39305	70374
1961	2432080	274080	293822	325128	315251	63510	44343	82914
1962	2520641	295389	321568	377012	326064	68368	50218	97023
1963	2608649	322266	359411	422274	336608	74099	57959	108916
1964	2732405	345230	394794	467474	352903	79079	65557	120953
1965	2905645	377718	426858	514210	380523	86254	72227	133480
1966	3133329	413324	465735	564139	419518	93463	80202	146607
1967	3362179	441345	510196	591404	456788	97835	88482	152467
1968	3652438	482558	549368	629757	500914	105146	95812	161572
1969	4040723	532790	612954	706916	559973	114983	108224	182344
1970	4410481	602922	696962	855774	612907	129205	125111	222517
1971	4859151	692042	790339	983568	669762	145897	143884	255237
1972	5308405	799877	898351	1085939	725404	164966	164840	278263
1973	5884643	963644	1046101	1207161	797432	195081	193464	304936
1974	6868229	1224864	1307866	1358685	933197	244699	240356	337837
1975	8077663	1557443	1566716	1467506	1095500	306061	282352	359305
1976	8819735	1848068	1849770	1582201	1199093	356496	328937	382765
1977	9781748	2148855	2129985	1698556	1336852	408080	373402	406829
1978	11190314	2468146	2446637	1843165	1542179	463598	422786	435899
1979	12801002	2945739	2827896	2037028	1776066	547223	480325	475857
1980	14637368	3610646	3359798	2283057	2041025	657343	560601	526042
1981	16604433	4075809	3898029	2487841	2320612	720557	634490	562492
1982	18036774	4292110	4571679	2655221	2504649	736189	724893	586854
1983	18571006	4551940	5151575	2799303	2534518	755120	796798	605058
1984	19398763	4874945	5658253	2961864	2612531	783847	856400	625114
1985	20450485	5299049	6090588	3100970	2717507	827383	908474	641808
1986	21658128	5703611	6476446	3236906	2823236	862860	956442	658262
1987	22641024	6166967	6828075	3376182	2906041	904660	1000803	675452
1988	23931846	6829224	7232980	3534513	3039286	972420	1056804	694898
1989	25176048	7732180	7697250	3748327	3175269	1065135	1120677	723041
1990	26313382	8518217	8218567	4055846				
1991	26945924	8869567	8809806	4377527				

Table A.7 *Business enterprise R&D expenditures (mln 1975 PPP$)*

	Total economy				Manufacturing			
	USA	UK	France	Germany	USA	UK	France	Germany
1955								
1956	3164	166	23	151				
1957	3864	200	33	198				
1958	4337	253	55	227				
1959	4999	281	80	277				
1960	5544	305	105	287				
1961	5746	352	131	433				
1962	6205	414	208	522				
1963	6939	456	308	624				
1964	7557	488	407	745				
1965	8151	531	524	932				
1966	9222	604	602	1072				
1967	9949	752	705	1213				
1968	11134	826	775	1367				
1969	12274	927	957	1620				
1970	12806		1091	2182				
1971	13688		1300	2779				
1972	15359	1435	1579	3104				
1973	17747	1829	1868	3480	17151	1668	1742	3194
1974	20820	2434	2450	4030	20122	2220	2279	3775
1975	24187	3612	3213	4839	23471	3283	2983	4424
1976	28703	5185	4112	5391	27804	4675	3818	4961
1977	33865	6946	4963	6015	32777	6243	4617	5549
1978	40671	9202	6196	7375	39171	8320	5788	6896
1979	50824	13348	7964	9003	48777	12262	7407	8221
1980	64698	18530	10448	10051	62060	17224	9722	9368
1981	82569	22769	13981	11100	79531	21305	12955	10319
1982	99295	25997	18444	12626	95109	24398	16998	11730
1983	114771	28402	22443	13643	108903	26613	20763	12686
1984	136767	32677	27569	14647	127799	30558	25580	13746
1985	159351	38636	32998	17086	146650	35666	30580	16030
1986	170293	46300	37175	18649	155855	39942	34367	17595
1987	184102	51727	41134	20373	168432	44317	38134	19340
1988	203291	59937	46082	21715	179643	51959	42460	20820
1989	220722	70999	53142	23546	190752	61103	48918	22609
1990	235540	79964	60144	24870	200754	69893	55517	24362
1991	249405	81758	65551	27576	206780	70920	60398	26400

Table A.8 *Number of total applications*

	Total economy								
	USA	UK	France	Germany		USA	UK	France	Germany
1940	60836	18254	7826	43479	1966	88525	58471	49486	67468
1941	52050	16847	11085	49855	1967	88164	59290	49341	67495
1942	44984	18642	14196	54386	1968	93471	61995	53656	65422
1943	44774	21944	14354	49060	1969	101415	63614	45393	66626
1944	54409	26200	11983		1970	103175	62107	47283	66132
1945	68052	35332	14856		1971	104729	61078	47971	65756
1946	81274	38181	23724		1972	99298	60281	47230	67354
1947	75669	35378	24768		1973	104079	60312	47234	66223
1948	68903	33626	22600		1974	102538	56250	43633	63545
1949	67811	33347	22441	76327	1975	101014	53400	40437	60095
1950	67556	31686	24800	130124	1976	102344	54561	39890	61705
1951	60670	30513	24377	60201	1977	100931	54423	39978	60401
1952	63391	33142	24198	59010	1978	101225	53751	40592	61304
1953	74036	36401	25861	60950	1979	101929	56159	43152	65060
1954	77503	37871	27823	59566	1980	106218	59643	45081	66768
1955	77502	37551	29051	54865	1981	108673	62356	47190	66926
1956	75211	39730	29047	53470	1982	112234	62721	47496	71262
1957	74298	40498	29512	53002	1983	106314	63207	49320	73288
1958	77629	42277	31448	54502	1984	114423	65936	53193	75326
1959	78708	44495	35315	56611	1985	116805	67409	54760	75681
1960	79721	44914	36446	57123	1986	122141	70116	57185	77408
1961	83396	46811	38310	58188	1987	133451	72700	60738	79050
1962	85180	49187	40063	59783	1988	146904	79968	66135	84923
1963	85869	51468	42449	61031	1989	161074	84788	72255	89656
1964	87592	53104	45286	64775	1990	175333	90978	78919	95164
1965	94629	55507	47793	66470	1991	176500	87608	76002	95193

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