Innovation and Growth: a survey of the empirical evidence

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Abstract: This paper surveys the empirical evidence on the link between innovation and economic growth in the light of New Growth Theory. It considers a number of different measures of innovation, such as R&D spending, patenting, and innovation counts, as well as the pervasive effect of technological spillovers between firms, industries, and countries. There are three main conclusions. The first is that innovation makes a significant contribution to growth. The second is that there are significant spillovers between countries, firms, and industries, and to a lesser extent from government-funded research. Third, that these spillovers tend to be localized, with foreign economies gaining significantly less from domestic innovation than other domestic firms. This suggests that although technological ‘catch-up’ may act to equalise productivity across countries, the process is likely to be slow and uncertain, and require substantial domestic innovative effort.

Keywords: Innovation, Spillovers, R&D, Patents, Growth Accounting, New Growth Theory.

Acknowledgements:

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JEL Classifications: O30, O47.
1 Introduction

The empirical study of economic growth has produced a voluminous and diverse literature. These studies take such a wide variety of approaches that it is difficult concisely to summarize their results. This paper reviews the empirical evidence on one important aspect of the growth process - the effect of innovation on growth. This is especially timely since Endogenous Growth Theory has challenged many existing views of the growth process. However, as we shall see, it is possible to reconcile these results within a simple endogenous growth model (see also Jones and Williams, 1997). This paper does not attempt to discuss the vast cross-country convergence literature (see Temple, 1998).

A number of externalities arise in the innovation process. First, the standing on shoulders effect of technological spillovers reduces the costs of rival firms because of knowledge leaks, imperfect patenting, and movement of skilled labour to other firms. Second, the surplus appropriability problem means that even if there are no technological spillovers, the innovator does not appropriate all the social gains from innovation unless she can price discriminate perfectly to rival firms (through licensing) and/or to downstream users. Third, the creative destruction effect means that new ideas make old production processes and products obsolescent. Fourth, stepping on toes occurs because congestion or network externalities arise when the payoffs to the adoption of innovations are substitutes or complements. This paper discusses the implications that these externalities have for the measurement of the effect of R&D on output.

The paper is structured as follows. Section 2 reviews the literature on the effect of R&D on output at the firm, industry and national level, and discusses how this literature can be interpreted in the light of Endogenous Growth Theory. Section 3 concentrates on the role of government-financed R&D. Section 4 looks at the effect of innovation more broadly defined and patenting. Section 5 discusses whether geography plays an important role in knowledge spillovers. Section 6 draws conclusions.

2 Studies of the effect of R&D spending

2.1 Theoretical Background

Serious study of aggregate production functions began with the work of Cobb & Douglas (1928), but it was not until Tinbergen (1942, not published in English until 1959) and Stigler (1947) that ideas such as total factor productivity and efficiency were introduced into the literature. Fabricant (1954) estimated that about 90 per cent of the increase in output per capita in the US between 1871 and 1951 was attributable to technical progress. The work of Douglas and Tinbergen on aggregate production functions, Kendrick...
Solow postulated an aggregate production function of the form:

\[ Y = F(K, L; t) \]

where \( Y \) represents output and \( K \) and \( L \) represent capital and labour inputs, with the variable \( t \) for time appearing in \( F(.) \) for technical change. Solow explicitly used the phrase 'technical change' for any kind of shift in the production function (including improvements in labour force education). When technical change is neutral, equation (1) can be re-written as:

\[ Y = A, f(K, L) \]

and by defining \( w_K = \frac{\partial Y}{\partial K} \cdot \frac{K}{Y} \) and \( w_L = \frac{\partial Y}{\partial L} \cdot \frac{L}{Y} \) as the elasticities of output with respect to capital and labour, and differentiating equation (2) with respect to time:

\[ \frac{\dot{Y}}{Y} = \frac{\dot{A}}{A} + w_K \frac{\dot{K}}{K} + w_L \frac{\dot{L}}{L} \]

if we now assume constant returns to scale (i.e., that \( wK + wL = 1 \)), and let \( Y/L = y \), \( K/L = k \), \( wL = 1 - wK \), and note that \( \dot{y}/y = \frac{\dot{Y}}{Y} - \frac{\dot{L}}{L} \), equation (3) becomes:

\[ \frac{\dot{y}}{y} = \frac{\dot{A}}{A} + w_K \frac{\dot{k}}{k} \]

which is easy to calculate from data on output per man hour, capital per man hour, and the share of capital in output, assuming competitive product and factor markets. Solow (1957) argued that American data, for the period 1909 to 1949, supported the following conclusions:

- Technical change during that period was neutral on average.
- The upward shift in the production function was, apart from fluctuations, at a rate of about one per cent per year for the first half of the period and 2 per cent per year for the last half.
- Gross output per man-hour doubled over the interval, with 87.5 per cent of the increase attributable to technical change and the remaining 12.5 per cent to increased use of capital.

The growth accounting approach was the dominant methodology for empirical studies of productivity after Solow’s (1957) groundbreaking paper until the early 1970s. Solow’s original conclusion, that technical progress accounted for almost all of economic growth, was gradually watered down as national accounts statistics and statistical methodology improved. Nonetheless, even recent studies (such as Jorgenson, 1990,
Denison, 1985, and Matthews et al., 1982) still suggest that the ‘growth residual’ accounts for a significant part of economic growth, usually around one-third.

The problem with all the studies in the strict Solow tradition, however, is that while they produce an estimate of the rate of technical progress, they do not shed any light on the causes of technical progress. Is it likely that economic growth would continue in the absence of increased workforce skill levels, investment in R&D and public infrastructure, the installation of capital equipment embodying new technologies, or changes in types and varieties of goods? More importantly, which of these, and many other factors, is the most significant cause of growth? These are the kinds of questions that Endogenous Growth Theory can potentially shed light upon (see Aghion and Howitt, 1998, chapter 12).

Table 1 presents estimates of the rate of growth of GDP and augmented joint total factor productivity (allowing for labour quality changes) over four time periods for six major economies. According to the table, the period 1950 to 1973 stands out as combining the fastest rates of GDP and augmented TFP growth. Seen in this historical context, the growth slowdown in the 1970s appears to be a return to the historical average growth rate. The table also confirms the stylised view that the performance of the UK has been particularly poor over the period.

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Note: The augmented joint factor productivity growth rate (AJFP) equals output growth (GDP) minus the contributions of the changes in quantity and quality of capital and labour.


Dissatisfaction with the neoclassical growth theory assumption that technical progress is exogenous led to both theoretical and empirical challenges from a fairly early stage. On the theoretical side, researchers such as Arrow (1962) and Kaldor and Mirrlees (1962) attempted to make the rate of technical progress endogenous. On the empirical side, researchers attempted explicitly to model the causes of total factor productivity growth by using data on R&D amongst other things. As we shall see, many of these empirical studies use models that can be interpreted as being within a framework that endogenizes the effect of innovation. However, their distinguishing characteristic is usually their pragmatic approach.
It is difficult to measure the innovative output of an industry. A variety of data is available, such as R&D spending, patenting, technological balance of payments, machinery imports and diffusion. Most researchers have chosen to use R&D spending as their measure of innovative input, often for reasons of data availability and reliability, rather than on explicit theoretical grounds. Studies by researchers such as Griliches (1980a), Mansfield (1980), Nadiri (1980a), Scherer (1982), and Terleckyj (1974) typically derived estimates of total factor productivity growth using a Cobb-Douglas production function, and then regressed these estimates against various measures of innovation input, normally research and development spending (either aggregated, or broken down into components such as basic and applied, private or government).  

A typical approach to the modelling of productivity and R&D is to assume a standard value-added Cobb-Douglas production function that includes the knowledge capital stock as a separable factor of production (see Griliches and Lichtenberg, 1984a). Consider the following equation:

\[ Y_t = A \cdot D_t^\beta \cdot K_t^{\alpha_1} \cdot L_t^{\alpha_2} \cdot e^{\mu t} \]

where \( Y_t \) equals output (value-added), \( D_t \) is the knowledge R&D capital stock, \( L_t \) is labour input, \( K_t \) is capital input, \( A \) is a constant, and \( \mu \) is a time trend which captures other trended influences. A measure of total factor productivity is:

\[ TFP_t = \frac{Y_t}{K_t^{\alpha_1} \cdot L_t^{\alpha_2}} \]

and assume constant returns to scale with respect to capital and labour, so \( \sum \alpha_i = 1 \). Typically, studies have taken \( \alpha_i \) to be the actual shares of labour and capital in total costs, thereby assuming that product and factor markets are competitive. Combining equations (5) and (6) yields:

\[ TFP_t = A \cdot D_t^\beta \cdot e^{\mu t} \]

or in logs:

\[ \log TFP_t = \log A + \beta \log D_t + \mu t \]

Differentiate equation (8) with respect to time and write \( \left[ d \log TFP_t \right] / dt = \dot{T} / T \):

\[ \frac{\dot{T}}{T} = \beta \frac{\dot{D}}{D} + \mu \]

from equation (5) we can interpret \( \beta \) as being the elasticity of output with respect to knowledge capital. That is:

\[ \beta = \frac{\partial \log Y}{\partial \log D} = \frac{\partial Y}{\partial D} \cdot \frac{D}{Y} \]

Hence one may rewrite (10) as:
\[
\frac{T}{T} = \frac{\partial Y}{\partial D} \cdot \frac{D}{Y} \cdot \frac{\dot{D}}{D} + \mu = \rho \frac{R}{Y} + \mu
\]

where \(\rho = \partial Y / \partial D\), and \(R = \partial D\) (i.e. net investment in knowledge capital).

In practice, estimates of the effect of innovation on total factor productivity can be obtained in two ways (see Griliches, 1991, and Griliches and Lichterberg, 1984a, for further discussion). The first is to use a measure of the stock of R&D capital in a regression of the level of total factor productivity, as shown in equation (12). The second is to use a measure of R&D intensity (relative to output) in a regression of the change in total factor productivity, as shown in equation (13):

(12) \[\log \text{TFP}_t = \log A + \beta \log D_t + \mu\]

(13) \[d \log \text{TFP}_t = \rho \frac{R_t}{Y_t} + \mu\]

where \(D_t\) is the stock of R&D capital and \(R_t\) is the flow of R&D. Equation (12) yields a measure of the elasticity of output with respect to knowledge (the parameter \(\beta\)), while equation (13) yields a measure of the social gross (excess) rate of return to knowledge (the parameter \(\rho\)), if \(R\) and \(Y\) are measured in the same units. The choice between the two approaches has largely been determined by the individual researcher’s access to different kinds of data and areas of interest, although equation (13) does not require any assumptions about the R&D capital stock (it does, however, assume that the return to R&D is constant).

There is a number of obvious problems with these two approaches, both theoretical and empirical. On the theoretical side, it is not clear that knowledge is separable in the production function. Furthermore, total factor productivity is usually calculated by subtracting labour and capital (and sometimes intermediate inputs) weighted by their shares in output, from output. Under perfect competition, factors of production are paid their marginal products, and their shares in output are therefore equal to their exponents in the production function (see Hall, 1990). Under imperfect competition, the measurement of total factor productivity will be biased.

On the empirical side, there are the usual measurement problems. These arise particularly in the construction of value-added and R&D data, and also with adjustments for cyclical utilization. Value-added data can be biased in a number of ways, the most important of which arises because of the use of a gross output deflator to construct real value-added (see Stoneman and Francis, 1992). Other problems arise because of the treatment of list prices and export prices (see Muellbauer, 1986). R&D data are problematic because of problems of definition, and the treatment of time-lags, depreciation, and inflation (see Griliches, 1988). It is also important to adjust for the cyclical nature of the total factor productivity data (see Muellbauer, 1986, and Cameron and Muellbauer, 1996).
2.2 Principal Empirical Results

A large number of studies in this tradition has been undertaken, at the level of individual firms, industries and countries. Table 2 summarizes the results of a large number of variants on equation (12), of which Griliches (1980a) is a good example. The majority of these studies found a strong and enduring link between R&D capital and output (typically, a 1% increase in the R&D capital stock is found to lead to a rise in output of between 0.05% and 0.1%).

Tables 3 and 4 summarize the results of a large number of variants on equation (13), of which Mansfield (1980) is a good example. These studies have also tended to find a strong and significant link between R&D and productivity growth, with the social gross (excess) rate of return to R&D being typically estimated as between 20% and 50%.10 As Griliches (1988) points out, because of knowledge spillovers, one would expect estimated rates of return at the industry level to be higher than at the firm level, but there is little evidence of this from tables 3 and 4.

One of the more important distinctions between the various studies is the extent to which they have attempted to model knowledge spillovers (the standing on shoulders effect). The benefits of R&D are widespread, so that each firm will benefit from both its own R&D, as well as the research results of other firms, the domestic science base and research carried out by foreign governments and foreign firms. Patents, scientific literature, technology licences, and technology embodied in capital and intermediate inputs, and personal contacts provide the means for research results to diffuse throughout the domestic and world economy. It is, however, difficult to measure these inter-industry and inter-firm spillover effects, and therefore difficult to incorporate them into TFP analysis. Furthermore, the results of government-funded R&D are usually made available at negligible cost, and are therefore certainly not priced correctly as inputs.

Since they do not know exactly where and to what extent the spillovers are occurring, researchers typically use some proxy for the flows of spillovers. In the literature, the matrices used to proxy the knowledge flows take four main forms: input-output tables, patent concordances, innovation concordances, and proximity analysis.11

Firms also accrue gains when they import technology from abroad. Foreign firms are unlikely to be able to appropriate all the (social) returns occurring in the importing country. This suggests that estimates of total factor productivity should account for foreign knowledge imports in some way. However, most studies of total factor productivity have been for the US, which is not usually considered to have been a major importer of foreign technology, although this may now be changing (see Eaton and Kortum, 1994, for example). For an open economy, however, foreign technology, both embodied in new capital and disembodied, is likely to be of importance. For this reason, Budd and Hobbis (1989) attempt to use
measures such as machinery imports and technological royalties to proxy the inflow of foreign knowledge. See Leduc and Silbertson (1986) for some discussion of the problems with such data.

Columns 3 and 4 of tables 3 and 4 present estimated indirect rates of return to R&D from the studies that attempted to model R&D spillovers. The results of these studies, whether using patent matrices or input-output tables to weight imported R&D, suggest that spillovers are pervasive and significant. Three further results of interest emerge from the studies summarized in tables 2, 3 and 4:

- The returns to process R&D are different from the returns to product R&D, with process R&D usually being found to yield higher returns (see Griliches and Lichtenberg, 1984b).
- The returns to basic R&D are different from the returns to applied R&D, with basic R&D typically yielding higher returns (see Griliches, 1986).
- The returns to R&D vary significantly between industries, with R&D in research-intensive sectors yielding higher returns, and that these inter-industry differences are more significant than inter-country differences. (see Englander, Evenson, and Hanazaki, 1988).

The extent to which the incentives to undertake R&D differ between industries can be illustrated simply. Table 5 shows the R&D intensities of the different manufacturing industries of the US, Japan, Germany, the UK and France. R&D intensity is defined as R&D divided by manufacturing value-added (the definition of R&D used here is Business Enterprise R&D, which reflects spending within industry, however financed, but excludes research undertaken by the government and the Higher-Education sector). Although there is a number of problems with this approach, the available data suggest that UK manufacturing is slightly less R&D intensive (spends less on BERD relative to manufacturing value-added) than its competitors. As table 5 shows, the R&D intensity of UK manufacturing is currently around 5%, compared with 6.4%, in West Germany, 6.5% in France, 6.6% in Japan, and 7.2% in the USA.

The R&D intensity of UK manufacturing has increased more slowly than in other G5 countries. In 1973, the UK R&D intensity was higher any country except the USA, but has since been overtaken by Japan, Germany and France. Furthermore, R&D intensity in the UK has been static during the 1980s, while other countries were increasing their efforts. To some extent this result is due to the data being for total BERD. The performance of the UK is relatively better if one considers only industry-funded BERD, since the government share of total BERD fell from 30 per cent in 1981 to 16 per cent in 1989.

On a sectoral basis, the UK spends a relatively high amount on R&D in the electronics (radio, television and communications) and pharmaceuticals industries, and a relatively low amount on R&D in aerospace and motor vehicles. UK spending in other high technology industries, such as computers, chemicals, and instruments, is only a little below the G5 average. There are significant weaknesses in a number of medium and low technology industries (such as textiles and metal goods).
Table 2
Estimates of the Output Elasticity of R&D

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Notes: Estimates derived from data on:

f: firm level; i: industry level; t: total economy; m: total manufacturing; p: private economy.

### Table 3

*Estimates of the Rate of Return to R&D in the USA*

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<td>0.11-1.11</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Bernstein-Nadiri (1989a)</td>
<td>0.09-0.20 (f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernstein-Nadiri (1989b)</td>
<td>0.07 (f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Griliches-Mairesse (1990)</td>
<td>0.24-0.41 (f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nadiri-Prucha (1990)</td>
<td>0.24 (i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernstein-Nadiri (1991)</td>
<td>0.15-0.28 (i)</td>
<td>0.20-1.10</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Lichtenberg-Seigel (1991)</td>
<td>0.13 (f)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wolff-Nadiri (1993)</td>
<td>0.11-0.19 (i)</td>
<td>0.10-0.90</td>
<td>Intermediate Inputs</td>
</tr>
</tbody>
</table>

*Notes: Estimates derived from data on:

\(f\): firm level; \(i\): industry level; \(t\): total economy; \(m\): total manufacturing; \(p\): private economy; \(r\): R&D-intensive sector.*

Table 4
More Estimates of the Rate of Return to R&D

<table>
<thead>
<tr>
<th>Study</th>
<th>Direct Rate of Return</th>
<th>Indirect Rate of Return</th>
<th>User Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canada</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globerman (1972)</td>
<td>0.00 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hartwick-Ewen (1983)</td>
<td>0.00 i</td>
<td>0.00</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Postner-Wesa (1983)</td>
<td>0.00 i</td>
<td>0.18</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Longo (1984)</td>
<td>0.24 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernstein (1988)</td>
<td>0.12 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hanel (1988)</td>
<td>0.50 i</td>
<td>1.00</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>M&quot;ohnen-Lepine (1988)</td>
<td>0.05-1.43 i</td>
<td>0.11-0.314</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Bernstein (1989)</td>
<td>0.24-0.47 i</td>
<td>0.29-0.94</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td><strong>Japan</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odagiri (1983)</td>
<td>0.26 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odagiri (1985)</td>
<td>(0.66)-0.24 i</td>
<td>0.00</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Odagiri-Iwata (1985)</td>
<td>0.17-0.20 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Griliches-Mairesse (1986)</td>
<td>0.20-0.56 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M&quot;ohnen-Nadiri-Prucha (1986)</td>
<td>0.15 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goto-Suzuki (1989)</td>
<td>0.26 i</td>
<td>0.80</td>
<td>Intermediate Inputs+Inv.Goods</td>
</tr>
<tr>
<td>Griliches-Mairesse (1990)</td>
<td>0.20-0.56 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suzuki (1993)</td>
<td>0.25 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>France</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Griliches-Mairesse (1983)</td>
<td>0.31 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hall-Mairesse (1995)</td>
<td>0.22-0.34 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>West Germany</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bardy (1974)</td>
<td>0.92-0.97 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M&quot;ohnen-Nadiri-Prucha (1986)</td>
<td>0.13 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O’Mahony-Wagner (1996)</td>
<td>0.00 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Belgium</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fecher (1989)</td>
<td>0.00 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Netherlands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bartelsman et al. (1996)</td>
<td>0.10-0.25 f</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UK</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M&quot;ohnen-Nadiri-Prucha (1986)</td>
<td>0.11 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sterlacchini (1989)</td>
<td>0.12-0.20 i</td>
<td>0.19-0.20</td>
<td>Intermediate Inputs</td>
</tr>
<tr>
<td>Sterlacchini (1989)</td>
<td>0.12-0.20 i</td>
<td>0.15-0.35</td>
<td>Innovation Flows</td>
</tr>
<tr>
<td>O’Mahony (1992)</td>
<td>0.08 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O’Mahony-Wagner (1996)</td>
<td>0.00 i</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>G5</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Englander-Mittelst&quot;adt (1988)</td>
<td>0.00-0.50 i</td>
<td>0.00-0.54</td>
<td>Patents</td>
</tr>
</tbody>
</table>

*Notes & Sources: as table 3.*
### Table 5

**DISAGGREGATED G5 R&D INTENSITIES 1973-1990**

<table>
<thead>
<tr>
<th></th>
<th>UK</th>
<th>FRANCE</th>
<th>GERMANY</th>
<th>JAPAN</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerospace</strong></td>
<td>43.0</td>
<td>33.4</td>
<td>19.5</td>
<td>45.9</td>
<td>26.2</td>
</tr>
<tr>
<td><strong>Electronics</strong></td>
<td>15.3</td>
<td>32.4</td>
<td>26.9</td>
<td>18.1</td>
<td>23.8</td>
</tr>
<tr>
<td><strong>Pharmaceuticals</strong></td>
<td>18.4</td>
<td>22.1</td>
<td>25.0</td>
<td>16.5</td>
<td>13.5</td>
</tr>
<tr>
<td><strong>Computers</strong></td>
<td>16.2</td>
<td>25.7</td>
<td>18.7</td>
<td>8.0</td>
<td>8.2</td>
</tr>
<tr>
<td><strong>Motor vehicles</strong></td>
<td>5.6</td>
<td>5.2</td>
<td>6.3</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td><strong>Chemicals</strong></td>
<td>5.9</td>
<td>6.3</td>
<td>7.5 b</td>
<td>4.3</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Instruments</strong></td>
<td>5.8</td>
<td>7.2</td>
<td>5.4 b</td>
<td>3.8</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Elec. mach. nes</strong></td>
<td>7.3</td>
<td>5.8</td>
<td>4.6</td>
<td>5.2 a</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Petroleum refining</strong></td>
<td>4.8</td>
<td>1.9</td>
<td>3.6</td>
<td>1.7</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Non-ferrous metals</strong></td>
<td>1.7</td>
<td>2.6</td>
<td>2.5</td>
<td>0.9</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Rubber &amp; plastics</strong></td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
<td>3.8</td>
<td>4.7</td>
</tr>
<tr>
<td><strong>Non-elec machinery</strong></td>
<td>2.3</td>
<td>2.6</td>
<td>1.5 b</td>
<td>1.9 a</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Stone, clay &amp; glass</strong></td>
<td>1.5</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Ferrous metals</strong></td>
<td>1.7</td>
<td>1.0</td>
<td>1.5</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Shipbuilding</strong></td>
<td>2.9</td>
<td>0.8</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Metal products</strong></td>
<td>0.6</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Textiles &amp; footwear</strong></td>
<td>1.0</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Wood &amp; furniture</strong></td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Paper &amp; printing</strong></td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total Manufacturing</strong></td>
<td>4.3</td>
<td>5.2</td>
<td>5.0</td>
<td>3.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>

**Sources:** OECD STAN database, UK Census of Production, OECD Industrial Structure Statistics.

**Notes:**
- R&D intensity is defined as Business Enterprise R&D (BERD) divided by value-added.
- a data not available for this year: data for nearest year used instead.
- b 1988 data.
- c includes computers.
- nes not elsewhere specified.
2.3 Standing on Shoulders or Stepping on Toes?

As noted earlier, there are four main mechanisms by which R&D causes externalities. These are through the effects of surplus appropriability, standing on shoulders, creative destruction, and stepping on toes. However, the approach taken by the all the empirical studies discussed above simply treats R&D as another form of investment and does not allow for the effect of these externalities. Therefore, we cannot tell immediately whether such studies under-estimate or over-estimate the effect of R&D.

Jones and Williams (1997) discuss exactly this problem. They derive an endogenous growth model in the spirit of Romer (1990a) which incorporates the four externalities discussed above. Their conclusions are rather surprising. They compare the estimate of the social return to R&D, \( \hat{\rho} \), produced by an equation such as (13), with the true social return from their model, \( \rho^* \), and obtain:

\[
\hat{\rho} = \rho^* - (1 - \lambda) \gamma_Y
\]

where 0<\( \lambda < 1 \) represents the *stepping on toes* effect of congestion externalities, and \( \gamma_Y \) is the growth rate of output. Therefore, \( \hat{\rho} \) represents an underestimate of the true social rate of return to R&D with a maximum downward bias equal to the rate of growth of output. However, if innovations are complements (that is, if \( \lambda > 1 \)), the productivity literature overestimates the rate of return. Nonetheless, the absolute magnitude of the error is small because it is multiplied by the growth rate of output, \( \gamma_Y \).

This result occurs because the return to society from the knowledge spillover (*standing on shoulders*) effect exactly offsets the capital loss to society due to the fall in the value of ideas, as ideas become less costly to produce as knowledge accumulates. The remaining term reflects the capital gain due to the increase in the value of designs resulting from the growth in R&D and \( \lambda < 1 \), reflected by the term \((1 - \lambda) \gamma_Y \). The distortions due to *surplus appropriability* and *creative destruction* do not affect either the rate of return calculation or the optimal amount of R&D.

It would be interesting to obtain an estimate of the value of \( \lambda \), the congestion parameter, especially since Stokey (1995) has pointed out that very few estimates of \( \lambda \) appear in the literature. Jones and Williams suggest the following method of estimating \( \lambda \). They find that the productivity literature’s estimate of the return to R&D is given by:

\[
\hat{\rho} = \frac{\lambda \gamma_{TFP}}{s_R}
\]

where \( \gamma_{TFP} \) is the rate of growth of TFP and \( s_R \) is the share of R&D in output. Re-arranging equation (15) yields:
Jones and Williams (1997) suggest that for the USA it is reasonable to take a lower bound for $\hat{\rho}$ of 30 per cent, and a lower bound for $s_R$ of 2.9 per cent, together with a lower bound for $\gamma_{TFP}$ of 1.8 per cent, which implies a lower bound for $\lambda$ of 0.48.

Given that the social returns to R&D are so large, it is interesting that more R&D is not undertaken. Jones and Williams also shed light on this problem, by comparing the competitive equilibrium in their model with the social planning solution. Recall that the surplus appropriability and standing on shoulders effects lead to under-investment; the creative destruction effect leads to over-investment; while the stepping on toes effect will lead to over-investment if innovations are substitutes and under-investment if they are complements.\textsuperscript{14} Jones and Williams calibrate their model to a range of plausible parameter values and conclude that the bulk of the excess returns to R&D (the excess return is equal to the social return minus the private return) are positive, but less than 20 per cent. Only when $\lambda$ is very small and the rate of interest very high does the decentralized economy over-invest in R&D. Taking into account the large degree of risk and uncertainty in the innovation process, as well as asymmetries in information between capital markets and R&D spenders, it does not seem surprising that large social returns to R&D can co-exist with relatively low rates of R&D investment.\textsuperscript{15} Jones and Williams conclude that the optimal amount to invest in R&D is about four times the actual amount invested by the USA.

### 3 Government-financed R&D

There is a fair amount of controversy on the effect of government financed R&D on productivity. On the one hand there is some evidence of spillovers between academic research and some types of government R&D and the private sector, although these spillovers are typically found to be smaller than those between firms themselves (Griliches and Lichtenberg, 1984a). Small firms (especially high-technology start-ups) may benefit more from these spillovers (Acs, Audretsch and Feldman, 1994). On the other hand there may be crowding out of private R&D because the government funding displaces private efforts (the extent of crowding out depends on whether the government finances applied or basic R&D). In addition, some have argued that government projects are often badly directed, although they are often targeted at social goals that private R&D would not undertake. In some sense these two arguments are contradictory since they imply that where government R&D is directed at market goals it merely crowds out private R&D, and that where it is directed at social goals it is simply mis-directed (of course, government R&D in areas such as defence may have large payoffs that are difficult to evaluate in money terms, such as freedom from invasion).\textsuperscript{16}
It is beyond the scope of this paper to analyse whether governments should support market-orientated R&D. There is a number of possible arguments for doing so: the four effects described by Jones and Williams (1997); because R&D is risky and uncertain; or because there may be market failures in financing. That the government should support projects with social goals, or that are ‘far from the market’, is less contentious. However, assessing the payoffs from such projects is likely to be difficult simply because they are unlikely to have rapid and direct effects on productivity.

Overall, the available evidence suggests that there are significant spillovers from government-funded R&D and from academic R&D. Adams (1990) finds that the output of the academic science base is a major contributor to productivity growth, but that there is lag in effect of roughly twenty years. The invention and application of the laser provides an example. The basic science underlying the laser was formulated by Einstein in 1916, but the first industrial uses occurred in the 1960s (see Rosenberg, 1994). Jaffe (1989) and Acs, Audretsch and Feldman (1992 and 1994) find that university R&D can have significant spillovers, with an elasticity of corporate patents with respect to university R&D of around 10 per cent. Nadiri and Mamuneas (1991) also find that government-financed R&D can have an impact on the productivity of manufacturing industry. Their results suggest a social rate of return to public R&D investment of around 10 per cent for US manufacturing, which is rather lower than the rates of return to private R&D reported in tables 3 and 4.

4 Innovation and Patenting

While the main focus of empirical research has been the effect of R&D on productivity, a few studies have looked at the roles played by other measures of innovation. Two good examples of such studies are Geroski (1989) and Budd and Hobbis (1989). Geroski (1989) examined the effect of entry and innovation on total factor productivity growth using a sample of 79 UK firms from 1976 to 1979 and argued that innovation (measured by the SPRU significant innovations database) accounted for 50 per cent of total factor productivity growth and entry for 30 per cent. Budd and Hobbis (1989) estimated a model of UK manufacturing productivity between 1968Q1 and 1985Q4. They found that patenting by UK firms in the US, and imports of machinery from abroad (assumed to embody the latest technology) have a significant and positive effect on productivity. However, the estimated contribution of imported machinery is very high, greater than the contribution of capital stock growth, and the authors suggest that this may be because the machinery imports variable may be picking up trending effects in output that they do not model explicitly.
A number of researchers have looked at the relationship between innovation and productivity at the firm level. These studies have met with mixed success. Studies such as Georghiou et al. (1986) and Baily and Chakrabati (1985) that used an interview or descriptive framework to look at the relationship between innovation and subsequent productivity growth have usually found that R&D played an important role. However, the scope of such studies has often been limited to a small number of firms or to particular innovations (the Pilkington float-glass invention is a frequently cited case).

Many researchers have also looked at the relationship between innovation and profitability. This is not central to the concerns of this paper, but it has often been difficult to establish a link between innovation and profits, mainly because the variety of factors affecting profits is greater than that affecting productivity. Geroski, Machin and van Reenan (1993) argue that for a sample of 721 UK firms between 1972 and 1983, innovation has a positive profit effect which is modest in size and that it is not possible to tell whether this is greater than the cost of R&D. They also found that innovative firms had higher profit margins in downturns, larger market shares, and were less sensitive to downturns than non-innovative firms. Furthermore, Stoneman and Kwon (1996) argue that firms that do not adopt new technologies experience reduced profits as other firms adopt new technologies.

5 Geography and Spillovers

From our earlier discussion it would appear that there are significant spillovers in the innovation process, both from the profit-seeking R&D of firms, and also from government funded R&D and academic research. It would also appear that these estimates can be reconciled with a simple endogenous growth model. An important question that arises is whether these spillovers are constrained geographically? If the spillover mechanism is primarily patent and journal publication, then geography is probably unimportant. However, if the mechanism involves personal contact and the flow of skilled labour and goods, then geography probably plays a significant role.

There is a large literature on the location of high-technology activity. Fingleton (1992 and 1994), for example, shows that high-technology manufacturing in the UK is not evenly distributed across the country. Marshall (1920) provides three reasons why industries appear to cluster.

- First, an industrial centre creates a pooled market for workers with specialized skills.
- Second, an industrial centre creates opportunities for a sophisticated intermediate goods industry to arise.
- Third, an industrial centre creates technological spillovers because knowledge flows locally more easily than at a distance.
In addition to these explanations based on external economies, Krugman (1991a and 1991b) argues that the presence of pecuniary externalities through market size effects, scale economies, and transport costs will also tend to cause the emergence of a core-periphery pattern in manufacturing.\textsuperscript{19} In short, industry will tend to form clusters because of strategic complementarities, some of which arise by chance.\textsuperscript{20}

Krugman (1991a) suggests two reasons that technological spillovers may be relatively unimportant. First, they cannot be measured because they leave a paperless trail. Second, that there is no evidence that high-technology industry in the USA is more localized than low technology industry. Krugman argues that there is likely to be a localization product cycle. At first production is localized to take advantage of Marshall’s three factors, but as production is standardized and becomes less skilled-labour intense, production can spread. If knowledge spillovers are more important in high-technology industries than in low-technology ones, we would expect that localization product cycle to be even more pronounced.\textsuperscript{21} Krugman constructs ‘locational Gini coefficients’ for a large number of US 3 digit manufacturing industries, and argues that these show that high-technology industry is no more localized than low-technology industry. However, a number of data problems suggests that his locational Gini coefficients are not a reliable index of relative localization.\textsuperscript{22}

What is the evidence on the localization of spillovers? There are three main strands of empirical evidence to be considered. The first is data on clusters of patents and innovations. The second is survey data on spillovers. The third is empirical evidence on estimates of international R&D spillovers in production functions.

5.1 Clusters of Patents and Innovations

Despite Krugman’s argument that technological spillovers leave no paper trail, a number of recent studies have managed to obtain data that provide important insights into the geography of innovation. Jaffe, Trajtenberg and Henderson (1993) compare the geographic location of patent citations in the USA with that of the cited patents.\textsuperscript{23} They find that citations to domestic patents are more likely to be domestic and more likely to come from the same state and metropolitan area as the cited patents, compared with a ‘control frequency’ calculated from the pre-existing concentration of research activity in the area. They reach a number of interesting conclusions. First, that citations are localized. Second, that localization fades over time (the 1980 citations are more localized than the 1975 citations). Third, they find little evidence that particular patent classes are more localized than others.\textsuperscript{24} Fourth, they find that 40 per cent of citations do not come from the same primary patent class, which is consistent with Jaffe’s (1986) conclusion that a significant proportion of spillovers arise from firms outside the receiving firm’s technological area.
Acs, Audretsch and Feldman (1994) use the US Small Business Administration (SBA) database on innovations in US manufacturing industry in 1982. Forty-six states plus the District of Columbia were the source of some innovative activity, with significant concentrations of innovative activity in eleven states, which accounted for 81 per cent of the 4200 innovations. The innovative output of all firms is found to be positively influenced by R&D expenditures within the state by private industry and by universities. Large firm innovations are particularly influenced by corporate R&D, while small firm innovations are particularly influenced by university R&D. Acs et al. argue that this suggests that small firms are able to generate significant numbers of innovations through exploiting knowledge created by R&D in university laboratories and large corporations.  

Audretsch and Feldman (1996) also examine the SBA innovation database, and attempt to determine whether innovative activity is more localized than productive activity. They calculate Gini coefficients for the geographic concentration of innovative activity and manufacturing value-added in each industry, and estimate regressions to explain the concentration of innovation using the concentration of value-added, as well as spending on corporate and university R&D within the state, and the use of skilled labour in the industry. After controlling for the effect of concentration of production, their results suggest that there is considerable evidence that industries where spillovers are most important (that is, where industrial and university R&D, and skilled labour, are most important) are more clustered than industries where spillovers are less important.

These three studies taken together suggest that there are important geographic aspects to knowledge spillovers. In summary, while Jaffe, Trajtenberg, and Henderson (1993) find that the distribution of patenting is more localized than the distribution of production, they did not explicitly model why this should be so. Indeed, they suggest that there is little evidence that individual patent classes are more clustered than others. This may be a result of the rather arbitrary nature of the patent classification system. Audretsch and Feldman (1996) find that the distribution of innovations is more localized than the distribution of production. They then showed that the technological intensity of the industries (measured by the ratios of corporate and university R&D to sales, and the proportion of skilled labour in the industry) can be used to explain that part of innovative localization that is not explained by production localization.

5.2 Surveys of Spillovers

Mansfield (1985) investigated how rapidly industrial technology leaks out with a survey of 100 American firms, chosen at random from all US firms with R&D spending over $1m in 1981. The survey was in two parts. First, to see how quickly a firm’s decision to develop a new product was known to its rivals. Second,
to see how quickly after development the nature and operation of the new product or process was known to its rivals. The sample suggests that, on average, the information concerning the decision to develop was in the hands of rivals within 12 to 18 months after it was made. News about process innovations leaked out somewhat slower than product innovations. Once the innovation has been developed, information concerning its operation is quickly known to rival firms. For product innovations the lag is 6 to 12 months, and for process innovations it is 12 to 18 months. This work supports the argument of Mansfield, Schwartz and Wagner (1981) that about 60 per cent of innovations were imitated within four years. Most importantly from our perspective, Mansfield (1985) also argues that it takes longer for innovations to diffuse from the USA to Europe than between US firms. This accords with Rosenberg’s (1982) argument that domestic R&D is necessary to adapt foreign ideas and that ideas diffuse more easily locally.

5.3 Estimates of International R&D Spillovers

Much attention has recently been given to the links between growth and trade (see Grossman and Helpman, 1991, and Aghion and Howitt, 1998). In the standard Hecksher-Ohlin model of trade, increased openness affects income by encouraging resource reallocation into sectors with a comparative advantage. In addition to this static effect of resource reallocation, openness has five potential dynamic effects on growth. These arise through the direct transfer of technology; the spillover of ideas; the elimination of the duplication of research; the increased size of the market; and increased competition. Authors such as Redding (1997) have gone on to argue that it is necessary to distinguish between a static comparative advantage (that is, the possession of a comparative advantage at the present time) and a dynamic comparative advantage (that is, the ability to acquire a comparative advantage in the future).

Internationally, Jeffrey Sachs and Andrew Warner (1995) suggest that trade openness is an important determinant of cross-country growth. They use a number of indicators to separate economies into those which are closed and open.29 On this basis they find that open economies converge to one level of income, while closed economies converge to another, following the twin peaks result discussed above. This suggests that openness is important because it allows poor countries to catch up with the rich, while being closed to trade suggests stagnation at the lower income level.30

The most important benefit to a country of participating in international trade might be the access that such trade affords to the technological knowledge of the rest of the world. Although agents in an economically isolated country might acquire information by reading professional journals, speaking to foreign experts, or inspecting prototype products, the contacts that develop through commercial exchange play an important role in the diffusion of knowledge. This argument can be justified in a number of ways. First, the larger the volume of trade, the greater the number of personal contacts between domestic and foreign individuals. These contacts may lead to the exchange of information. Second, imports may embody innovations that are
not available in the local economy, and that local researchers may gain insights from these innovations. Third, when local goods are exported, foreign purchasing agents may suggest ways to improve the production process. It seems likely therefore that the extent of knowledge spillovers will increase with the extent of trade.\textsuperscript{31} One further important channel for knowledge spillovers is foreign direct investment (FDI), which has played an increasing role in world trade over the past twenty years. The pattern of FDI in East Asia suggests strongly that it is an important source of technical knowledge to recipient countries.\textsuperscript{32}

Of course, knowledge spillovers across countries are not perfect. This is suggested by the work of David Coe and Elhanan Helpman, who investigate the role of international trade in R&D spillovers, and find that the benefits of R&D are shared across national borders. They found that small countries tend to benefit more from R&D undertaken abroad. Each 1 per cent increase in trading partners R&D capital stock leads to a 0.07 per cent increase in UK total factor productivity, while a 1 per cent increase in the UK R&D capital stock leads to a 0.23 per cent increase in UK productivity. In contrast, a 1 per cent increase in the R&D capital stock of its trading partners raises the productivity of the Republic of Ireland by 0.15 per cent, while a 1 per cent rise in its own R&D capital stock raises its productivity by 0.07 per cent. Their estimates imply large international R&D spillovers, with about one-quarter of the benefits of R&D in a G7 country accruing to its trading partners.\textsuperscript{33} Furthermore, Coe and Helpman have shown that the countries that gain the most from foreign R&D are those whose economies are most open to foreign trade.\textsuperscript{34}

Lichtenberg (1992) used the Summers-Heston (1988) dataset and extended it to include the effect of private and government-funded R&D as well as fixed and human capital. For a cross-section of fifty three countries, he found that labour productivity growth between 1960 and 1985 was positively influenced by the ratio of private R&D to GNP. The estimated social rate of return to private R&D investment is about seven times as large as the return to physical investment, with an elasticity of output with respect to private R&D of around 7 per cent (cf. Coe and Helpman, 1995). The social return to government-funded R&D is found to be much lower than that of private R&D. Lichtenberg also argues that his findings suggest that international spillovers of technical knowledge are neither complete not instantaneous.\textsuperscript{35}

The recent theoretical literature on endogenous growth provides three main proximate mechanisms through which openness may affect growth (see Cameron, Proudman and Redding, 1998). International openness may affect either the domestic rate of innovation, or the amount of technology that can be transferred, or the rate of adoption of technologies from more advanced countries. For the UK, there is evidence that openness and productivity growth are closely associated, but also that openness increases the rate of adoption of technology from the USA (see Proudman and Redding, 1998).

If international knowledge spillovers are incomplete or slow, one might expect relative productivity levels in different countries to look like random walks. An interesting paper by Evans (1996) suggests that the opposite has occurred, suggesting that the advanced industrial countries are growing at the same rate in the
long-run. However, there is other evidence that suggests that rates of technological progress may differ across industrial countries (see Lee, Pesaran & Smith, 1997) or that some sectors are converging while others are not (see Bernard and Jones, 1996). The cross-country convergence literature is too large to summarize neatly here, and readers are directed to the excellent survey by Temple (1998).

6 Conclusion

Neoclassical growth theory postulates that technical progress is exogenous and proceeds at a steady rate (see Solow, 1956, and Swan, 1956). This is a ‘manna from heaven’ view of technology. Early studies of the effect of innovation on productivity did not attempt explicitly to model technical progress, but nonetheless concluded that it played a significant role in productivity growth (Solow, 1957). With technical change apparently being so important to growth and with the assumption that it is exogenous being so intuitively and theoretically untenable, it was natural that researchers should attempt to examine technical progress in an endogenous framework. At first, the pace of empirical work moved faster than theoretical work as researchers found that measures of the profit-maximising choices of agents (such as R&D spending) could help to explain productivity growth. Most of the empirical work in the 1970s and early 1980s was theoretically agnostic in its approach, and it was not until interest in the theory of economic growth began to revive in the 1980s that researchers began to produce models that successfully endogenized the rate of technical change.

There has been a vast amount of research into the effect of innovation on productivity. A consensus has emerged that innovation has a significant effect on productivity at the level of the firm, industry and country, whether measured by R&D spending, patenting, or innovation counts. Griliches (1988) suggests that the elasticity of output with respect to R&D is usually found to be between 0.05 and 0.1, and that the social rate of return to R&D is between 20 and 50 per cent. Furthermore, attempts to model the spillovers that occur in the innovation process have usually found that these spillovers are large and significant. While much of the productivity literature predates endogenous growth theory, the recent work of Jones and Williams (1997) suggests that it is possible to reconcile the estimates obtained with more complex theoretical models that incorporate a variety of externalities to R&D. Furthermore, Jones and Williams suggest that the optimal level of R&D would be about four times its current level in the US.

Neoclassical growth models suggest that levels of output and growth rates of countries and regions should converge over time. Endogenous growth models (such as Grossman and Helpman, 1991) tend to produce more complex results where convergence does not occur, or even where there is divergence. The empirical evidence on this issue is also mixed. Economists even find it difficult to agree on how convergence should be measured. Many would agree that there is some kind of conditional convergence process at work in the
world economy, which means little more than that countries with similar characteristics will converge to similar levels of income per capita. Danny Quah is a notable critic of much of the convergence literature. He argues that the key issue is not whether a single economy is tending towards its own steady-state but what happens to the entire cross-sectional distribution of economies. He goes on to argue that the distribution is polarizing into twin peaks of rich and poor countries. Some have argued that openness to trade appears to be playing a role in the development of this bimodality and that more open economies are more likely to be in the higher income convergence club. Fagerberg (1994) argues that while ‘catch-up’ growth is possible, it can only be realized by countries that have a sufficiently strong ‘social capability’ in investment, education, and R&D. 

Many studies have argued that spillovers are likely to be localized and that the adoption of foreign technology may require substantial investments in innovation (Rosenberg, 1982). Further light has been shed on the effect of geography on spillovers by recent work by Jaffe et al. (1993), Acs et al. (1994), and Audretsch and Feldman (1996). Their work suggests that technologically-intensive industries tend to be more localized than other industries, and that information flows locally more easily than at a distance. This suggests that personal contacts, whether at conferences, trade fairs, seminars, or sales meetings, are a significant transmission mechanism. Along similar lines, Grossman and Helpman (1991) have argued that one of the main benefits of international trade is that it creates personal contacts with other countries.

Overall, the evidence in this paper suggests that international technological spillovers, while important, cannot account for most productivity growth in a mature economy. It is the innovative efforts of domestic firms and organizations that are most important, and whose efforts spill over most easily to other domestic firms. As we have seen, there are at least three reasons for this. First, a substantial domestic research effort is necessary to exploit the results of foreign research. Second, because of secrecy, geographic, and cultural barriers to diffusion, foreign research results take longer to diffuse to the domestic economy, if they diffuse at all, than domestic research. Third, domestic research, especially in Higher Education, plays an important role in human capital formation.
References


Mansfield (1985) shows that knowledge of innovations leaks between firms relatively quickly. Griliches (1992) argues that the extent to which this effect exists and can be measured is dependent upon the competitive structure of the innovating and downstream industries, and whether the price indices used in the national accounts allow for ‘quality’ changes. Aghion and Howitt (1992) present a model of growth through creative destruction. David (1985) and Katz and Shapiro (1994) argue that innovations are complements, while Dasgupta and Maskin (1987) argue that they are substitutes. See also Fudenberg and Tirole (1984). Hogan (1958) raised early doubts about Solow’s methodology and statistical sources. See Griliches (1996) for more on the history of the ‘growth residual’. See also Englander and Mittelstädt (1988) who examine productivity growth in twenty one OECD countries. Not all studies have used Cobb-Douglas production functions. Some used other Constant-Elasticity of Substitution or translogarithmic production functions, while others used a cost function approach (see Möhlen, 1994). The R&D capital stock is usually constructed as a perpetual inventory of real R&D spending, with some arbitrary choice of depreciation rate. In practice, as Hall and Mairesse (1995) point out, total factor productivity regressions are usually insensitive to the depreciation rate chosen. Schankerman (1981) pointed out that the labour and capital components of R&D are ‘double-counted’ in total factor productivity regressions because they appear once in the traditional measures of labour and capital, and once again in the R&D expenditure input. This ‘Excess Returns Interpretation’ means that the calculated elasticity of R&D is either a risk premium or a supra-normal profit on R&D investment, and that the rate of return to R&D is a social gross (excess) rate of return. As is apparent from equations (13) and (14), the return to R&D can be expressed as a function of the output elasticity of R&D, so that 
\[
\rho = \beta \cdot (Y / D) .
\]
Srinivasan (1996) reviews the spillover measurement issues, and uses a parametric method to estimate spillovers between high-technology sectors. He argues that few previous studies have successfully separated the effects of own-R&D, spillover R&D, and exogenous technical progress. See Capron et al. (1996) for further discussion of inter-industry technological spillovers. See Englander, Evenson, and Hanzaki (1988), for example. Verspagen (1995) estimates translogarithmic production functions for pooled groups of 15 industries in 9 principal OECD economies. The three pools of five sectors correspond to high, medium and low-technology groups. He finds that the influence of R&D on output is only significant in the high-technology sector, and that differences between countries are less significant than differences between sectors. They omit capital market imperfections, but this should strengthen their results since Stiglitz (1992) and Hall (1993) argue that such imperfections promote under-investment. If innovations are complements then there will be a network externality to R&D such as that proposed by David (1985) and there will be under-investment. If innovations are substitutes, such as if research projects are excessively similar in the model of Dasgupta and Maskin (1987), there will be congestion externalities and hence over-investment in R&D. In practice, some research projects in some industries will be complements, while others will be substitutes. Bartelsman et al. (1996) apply the Williams and Jones framework to firm-level data on Dutch manufacturing and conclude that the private rate of return probably under-estimates social returns by only a few percentage points. Mairesse and Hall (1996) examine the effect of R&D on productivity in a panel of French and US manufacturing firms. They conclude that R&D earned a normal private rate of return in the US during the 1980s. This accords with Hall’s earlier finding (1993) that the stock market valuation of US R&D capital fell by a factor of four during the 1980s, perhaps reflecting these low private returns. Hartley and Singleton (1990) review the issue of whether defence R&D crowds out private R&D. See Poole and Bernard (1992) for a sceptical view of the civil spillovers from defence R&D. Berman (1990) discusses the increasing importance of industrial funding for research carried out in Universities, and argues that direct industry funding of R&D leads to increases in the R&D expenditure of industry itself. See Office of Science and Technology (1993) for a survey of the effects of government-funded R&D. See also Papagni (1992) on patterns of high-technology specialisation across the European Union. Interestingly, Marshall and Krugman’s explanations of clustering are sometimes similar to Porter’s (1991) explanations of national competitive advantage.

Arrow (1962), among others, argued that spillovers are likely to be more important in high-technology industries than low technology ones.

Data confidentiality problems lead to the exclusion of the aerospace and photographic equipment industries from the data, and because only three-digit data are available, the computing industry is classified within the ‘electronic components industry’.

A significant point to remember is that the distribution of value of patents is highly skewed - most patents have almost no economic value, while a few are of exceptional value (see Schankerman and Pakes, 1986).

In contrast, Cantwell (1990) finds evidence that the geographic concentration of patenting in the USA is higher in technologically intensive industries.

Pavitt et al. (1987) show that the relationship between innovation and firm size is usually non-linear, being high for small and large firms, but lower for medium sized firms. There is often thought to be a problem with small firm innovation data because there will be a large number of zero innovation counts, see Blundell, Griffith, and van Reenan (1995). Cohen and Klepper (1996) argue that there is no advantage to firm size in conducting R&D.

This approach is similar to that of Jaffe et al. (1993) discussed above, but using innovations rather than patents.

The measure of skilled labour is the proportion of 1970 employment accounted for by professions and kindred workers, plus managers and administrators (except farm) plus craftsmen and kindred workers. In a different context, Machin (1994) presents evidence that this is likely to be a good proxy for skilled labour.

See Audretsch and Stephan (1996) for evidence that geographic proximity is not a major influence on the transfer of knowledge from university laboratories to companies in the US biotechnology industry.

They define a closed economy as one where non-tariff barriers cover over 40 percent of trade; or average tariff rates are over 40 percent; or which has a black market exchange rate which depreciated by more than 20 percent relative to the official rate; or a socialist economic system; or a state monopoly on exports.

This result is also found by the more sophisticated analysis of Proudman, Redding, and Bianchi (1997).

This analysis could apply to geographically distinct regions just as much as to politically distinct countries, although some writers, such as Mancur Olson (1991), would argue that the institutional structure of a country is more important in determining its learning capabilities than its geography.

See Cameron (1998) for a discussion of foreign direct investment.

Coe, Helpman and Hofmaister (1997) extend the analysis to look at the effect of R&D and trade on growth in the developing world. Since reliable R&D data are rarely available for such countries, they construct a proxy variable by weighting the R&D stocks in the OECD nations according to their trade flows with each developing country. They find that this variable, showing the joint influence of technology and trade, has a significant effect on growth in developing countries.

Keller (1998) has presented a sceptical view of Coe and Helpman’s results.

One important problem with Lichtenberg’s results is the quality of the R&D data available for the smaller countries.

A huge number of different characteristics have been examined in this literature, ranging from the average number of years of schooling to the distance from the equator. A good summary of the variables is provided by Xavier Sala-I-Martin (1997). Among the most robust of these variables are the share of physical investment in output, the level of human capital, and the degree of openness to trade. Most studies have major problems because they do not adequately allow for endogeneity, that is, fast growth may cause high investment, rather than vice-versa.

See Temple and Johnson (1998) for more on social capability and growth.