CENTRE FOR ECONOMIC PERFORMANCE

DISCUSSION PAPER NO.277

February 1996

INNOVATION AND ECONOMIC GROWTH

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ABSTRACT

This paper surveys the empirical evidence on the link between innovation and economic growth. 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.

This paper was produced as part of the Centre's
Programme on Corporate Performance and Work Organisation

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FEBRUARY 1996

Published by
Centre for Economic Performance
London School of Economics and Political Science
Houghton Street
London WC2A 2AE

ISBN 0 7530 0300 7

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The Centre for Economic Performance is financed by the Economic and Social Research Council.

ACKNOWLEDGEMENTS

I am grateful to Bronwyn Hall, John Muellbauer, Stephen Nickell, Robin Nuttall, Stephen Redding, and Grahame Walshe for helpful comments and discussions. Nonetheless, all errors and opinions are my own.

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1. Introduction

The theoretical and 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 to summarise their results concisely. This paper reviews the empirical evidence on one very important aspect of the growth process - the effect of innovation on growth.

Any serious study of the literature on technical progress and growth must start with the work of Solow (1957) who derived estimates of US total factor productivity between 1909 and 1949. His startling conclusion was that technical change (the whole of the so-called ‘residual’ was attributed to technical change) was responsible for the majority of economic growth during the period. However, later work by researchers in this growth accounting tradition, such as Denison (1962) and Jorgenson and Griliches (1967), who adjusted for changes in labour quality and for various measurement errors, reduced the residual to around one third of economic growth.

Uneasy with the neo-classical growth accounting assumption that all of total factor productivity growth is caused by exogenous technical change, other researchers attempted to augment the neo-classical model by explicitly modelling the time series of total factor productivity by using data on innovation. There can be no single measure of the output of the innovation process. Indicators such as Research and Development (R&D) spending, patenting, technological balance of payments, machinery imports, and diffusion all jostle for recognition. Most researchers have chosen to use R&D spending as their measure of technical change, usually because R&D spending data are easiest to compile and most reliable.

Studies by researchers such as Griliches and Mansfield 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 R&D spending (either aggregated, or broken down into components such as basic and applied, private or government). Industry-funded R&D spending is usually found to be most significant, with government-funded R&D making a smaller contribution. While the majority of these 'innovation-augmented growth accounting 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%), they have usually been rather stronger on data analysis than on econometric methodology. This is not surprising given the age of many of the papers.

Recent theoretical work has tried fully to endogenise the role of innovation in the growth process. These theoretical studies have considered four main kinds of innovation - learning by doing (see Romer, 1986); human capital (Lucas, 1988); R&D (Romer, 1990a, and Aghion and Howitt, 1992); and public infrastructure (Barro, 1990). It is difficult to generalise about the empirical approaches taken by the papers that explicitly attempt to test New Growth Theories. They typically attempt to test whether the elasticity of output with respect to broad capital (measured in one of the four ways mentioned above) is higher than its share in value-added or gross-output. Following Romer (1987) many of the papers focus on the evidence of a cross-section of countries both because data is readily available (particular the Summers-Heston, 1988, dataset) and because Romer (1987) argued that high-frequency data is not suitable for such analysis. Empirical studies in the endogenous growth tradition tend to suggest that technological spillovers are an important component of the growth process (see Coe and Helpman, 1993, for example).

There are externalities in innovation because firms are unable fully to appropriate the gains from their own innovation. The externalities occur in three main ways. First, technological spillovers reduce the cost of rival firms because of knowledge leaks, imperfect patenting, and movement of skilled labour to other firms.[1] Second, network externalities may arise because the payoffs to the adoption of innovations may be complementary.[2] Third, 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.[3]

The paper is structured as follows. Section 2 reviews the literature on the effect of R&D, innovation, patents and technological spillovers at the firm, industry and national level. Section 3 discusses whether geography plays an important role in spillovers. Section 4 draws conclusions.

2. Spillovers and the Returns to R&D, Innovation, and Patenting

2.1. Studies of the effect of R&D spending

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% 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 (1956) on national accounts data, and also Abramovitz (1956), was synthesised into a coherent empirical whole by Solow (1957), who suggested that technical change was responsible for the majority (87.5%) of economic growth.[4]

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 technical progress is responsible 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?

Table 1 (taken from Maddison, 1987) 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.[5]

Dissatisfaction with the neo-classical 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), Kaldor and Mirrlees (1962), Uzawa (1967), and Conlisk (1969) 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 innovation. 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 technical change, often for reasons of data availability and reliability, rather than on 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 approach, 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).[6]

In practice, estimates of the effect of innovation on total factor productivity can be obtained in two ways.[7] 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 1.[8] 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 2.

$$\log TFP_t = \log A + \gamma \log RDK_t + \beta t \quad \textbf{(1)}$$

$$d \log TFP_t = \rho \frac{RD_t}{Q_t} + \beta \quad \textbf{(2)}$$

where RDK is the stock of R&D capital and RD is the flow of R&D. Equation 1 yields a measure of the elasticity of output with respect to knowledge (the parameter γ), while equation 2 yields a measure of the social gross (excess) rate of return to knowledge (the parameter ρ).[9] 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 2 does not require any assumptions about the R&D capital stock.

There are 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 and furthermore, factors of production are not always paid their marginal products, so the factor-share assumptions inherent in the calculation of total factor productivity may be invalid.[10] 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 utilisation.[11]

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 1, 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 3a and 3b summarize the results of a large number of variants on equation 2, 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%. 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 3a and 3b.

Given that the apparent returns to R&D to individual firms are so large, it is interesting that more R&D is not undertaken so that the return is driven down to its competitive level. That this does not occur is presumably the result of the large degree of risk and uncertainty in the innovation process, as well as asymmetries in information between capital markets and R&D spenders. Three further results of interest emerge from the studies summarized in Tables 2, 3a and 3b. The first is that 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 second is that 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 third is that 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).

One of the more important distinctions between the various studies is the extent to which they have attempted to model knowledge spillovers. 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. Because we 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 flows take four main forms: input-output tables, patent concordances, innovation concordances, and proximity analysis.

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. 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 Ledic and Silbertson (1986) for some discussion of the problems with such data.

Columns 3 and 4 of Tables 3a and 3b 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.

2.2. Studies of the Effect of Innovation and Patenting

The main focus of empirical research has been the effect of R&D on productivity, and relatively few studies have looked at the role 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% of total factor productivity growth and entry for 30%. Budd and Hobbis (1989) estimated a long-run model of UK manufacturing productivity between 1968Q1 and 1985Q4, using a cointegrating methodology. 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).

A number of researchers have also looked at the relationship between innovation and profitability. This is not central to our concerns here, but we can say that 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, but that innovative firms had higher profit margins in downturns, larger market shares, and were less sensitive to downturns than non-innovative firms. Further references to the literature are contained in Geroski, Machin and van Reenan (1993).

2.3. Studies of the effect of 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, 1993). 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 funds 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, however, critics of government R&D cannot have it both ways - they would argue 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 misdirected (of course, government R&D in areas such as defence may have large payoffs that are difficult to evaluate in money terms[12]). It is beyond the scope of this paper to analyse whether governments should support market-orientated R&D. There are a number of possible arguments for doing so - R&D is risky and uncertain; has public goods qualities; and 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 quick and direct effects on productivity.

Overall, the available evidence suggests that there are spillovers from government-funded R&D and from academic R&D.[13] 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 1993) find that university R&D can have significant spillovers, with an elasticity of corporate patents with respect to university R&D of around 10%. 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% for US manufacturing.

3. 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. 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, but if the mechanism involves personal contact and the flow of skilled labour, 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 spread across the country.[14] Marshall (1920) provides three reasons why industries appear to cluster. First, an industrial centre creates a pooled market for workers with specialised 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.[15] In short, industry will tend to form clusters because of strategic complementarities, some of which arise by chance (Krugman, 1991c; Kaldor, 1970; and Arthur, 1989).[16]

Krugman (1991a) suggests two reasons that technological spillovers are relatively unimportant. First, because they leave a paperless trail they cannot be measured. 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 standardised and becomes less 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.[17] 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.[18]

What is the evidence on the localization of spillovers? There are four 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 R&D spillovers in production functions. The fourth is the empirical evidence on convergence.

3.1. Clusters of patents and innovations

Krugman (1991a) argues that technological spillovers leave 'no paper trail' by which they can be measured, and are therefore of less interest than other factors in producing localization. However, a number of recent studies have managed to obtain data that provides 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.[19] 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.[20] Fourth, they find that 40% 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 (1993) 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% 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.[21]

Audretsch and Feldman (1994) also examine the SBA innovation database, and attempt to determine whether innovative activity is more localized than productive activity.[22] 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[23]. 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. While, Jaffe, Trajtenberg, and Henderson (1993) find that the distribution of patenting is more localised 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 (1994) 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.[24]

3.2. 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. Firstly, to see how quickly a firms' decision to develop a new product was known to its rivals, and secondly, 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, with process innovations leaking 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% 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, and the evidence presented by Bernstein and Möhnen (1994) that Japanese and US R&D are complements.

3.3. Estimates of international R&D spillovers

Grossman and Helpman (1991a) argue that 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. They argue that 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.[25] It seems likely that the extent of knowledge spillovers will increase with the extent of trade (see Grossman and Helpman (1991b) for a formal model of this).[26]

Coe and Helpman (1993) investigate the role of international trade in R&D spillovers, and find that the benefits of R&D are shared across national borders. Each country benefits from its own R&D as well as that of its trading partners. Coe and Helpman examine the relationship between total factor productivity and cumulative spending on R&D in 22 advanced economies from 1970 to 1990. They also measure the amount of R&D imported from abroad by each country by measuring the cumulative R&D conducted by its trading partners, weighted according to trading patterns. They find that domestic R&D has a positive and significant effect on productivity in all 22 economies, with the effect being largest in the G7.

They find that small countries tend to benefit more from R&D undertaken abroad. Each 1% increase in trading partners R&D capital stock leads to a 0.07% increase in UK total factor productivity, while a 1% increase in UK R&D capital stock leads to a 0.23% increase in UK productivity. In contrast, a 1% increase in the R&D capital stock of its trading partners raises the productivity of the Republic of Ireland by 0.15%, while a 1% rise in its own R&D capital stock raises its productivity by 0.07%. All these 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.[27] Furthermore, Coe and Helpman argue that the countries that gain the most from foreign R&D are those whose economies are most open to foreign trade.

Lichtenberg (1992) uses the Summers-Heston dataset and extends it to include the effect of private and government-funded R&D as well as fixed and human capital. For a cross-section of 53 countries, he finds that labour productivity growth between 1960 and 1985 is 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% (*cf* Coe and Helpman, 1993). The social marginal product of 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 nor instantaneous.[28]

3.4. Evidence on the convergence hypothesis

Neo-classical growth models of closed economies (such as Ramsey, 1928; Solow, 1956; and Swan, 1956) suggest that per capita growth rates should be inversely related to initial levels of income. If economies are similar in their preferences and technology parameters, poor countries should grow more rapidly than rich ones. This theory is often used to support the argument that levels and growth rates of income should converge over time for countries and regions. However, endogenous theories of growth tend to produce a much more complex set of results. Grossman and Helpman (1991a: chapter 8) present a model of endogenous specialization and trade in a world economy with national spillovers of knowledge, and conclude that a country that begins with a head start will often widen its lead over time. Exact results depend on preferences, the relative sizes of the countries involved, and whether there is government intervention. Similarly, Boldrin and Rustichini (1994) present a model of an economy with two sectors of production where a positive external effect induces a two-dimensional manifold of equilibria converging to the same steady state (in the case of bounded capital accumulation) or to the same constant growth rate (in the unbounded case). For the latter case it is possible that persistent fluctuations in growth rates are possible.[29]

The empirical evidence on convergence tends to suggest that some degree of convergence does operate but over rather long periods. De Long (1988), Romer (1987), and Benhabib and Jovanovic (1991) find little empirical evidence of convergence in regressions relating the rate of growth of GDP to the initial level of GDP for a cross-section of a large number of countries (*cf* Dowrick and Nguyen, 1989). However, when Barro (1991) and Mankiw, Romer and Weil (1992) include human capital (secondary school enrolments), they find evidence of conditional convergence, as do Levine and Renelt (1992). Overall, there is reasonable evidence that a group of countries is converging.[30] Furthermore, the rates of convergence found by regional studies of the US states, such as Holtz-Eakin (1992) and Barro and Sala-i-Martin (1991; 1992), and of regions of Japan, Europe, Spain and Canada by Sala-i-Martin (1994), suggest that regions tend to catch-up somewhat faster than countries.[31]

4. **Conclusions**

In the traditional theory of economic growth, productivity is driven by exogenous (that is, unexplained) technical progress, and productivity levels and growth rates should converge over time.[32] In contrast, new theories of economic growth argue that the rate of innovation is the result of the profit-maximising choices of economic agents, and that it is therefore possible for there to be permanent differences in productivity levels and growth rates. This paper has reviewed the evidence on these issues.

Neo-classical growth theory postulates that technical progress is exogenous and proceeds at a steady rate. This is the so-called ‘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 (such as Terleckyj, 1974) moved faster than theoretical work and 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, whether measured by R&D spending, patenting, or innovation counts, innovation has a significant effect on productivity at the level of the firm, industry and country. 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%. Furthermore, attempts to model the spillovers that occur in the innovation process have usually found that these spillovers are large and significant.

Neo-classical growth models (such as Solow, 1956) also suggest that levels of output and growth rates of countries and regions should converge over time. Endogenous growth models (such as Grossman and Helpman, 1991a) 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. De Long (1988) and Romer (1987) find little empirical evidence of convergence in regressions relating the rate of growth of GDP to the initial level of GDP for a cross-section of a large number of countries. However, when Barro (1991) and Mankiw, Romer and Weil (1992) include human capital (secondary school enrolments), they find evidence of conditional convergence, as do Levine and Renelt (1992). Surveying the evidence, 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* (1993), and Audretsch *et al* (1994). 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 (1991a) have argued that one of the main benefits of international trade is that it creates personal contacts with other countries.

The evidence, therefore, suggests that international technological spillovers, while important, cannot account for most productivity growth. It is the innovative efforts of domestic firms and organisations 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.[33]

ENDNOTES

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[1] Mansfield (1985) shows that knowledge of innovations leaks between firms relatively quickly.

[2] See David (1985) and Katz and Shapiro (1994).

[3] Griliches (1991) argues that the extent to which this third 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.

[4] Hogan (1958) raised early doubts about Solow's methodology and statistical sources.

[5] See also Englander and Mittelstädt (1988) who examine productivity in twenty one OECD countries.

[6] Some studies use a Dual representation of technology, rather than Cobb-Douglas (see Möhnen, 1994).

[7] See Griliches and Lichtenberg (1984a) and Cameron and Muellbauer (1995) for a fuller exposition.

[8] The R&D capital stock is usually constructed as a perpetual inventory of 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.

[9] Schankerman (1981) has 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.

[10] 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.

[11] 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, 1984). R&D data are problematic because of problems of definition, and the treatment of time-lags, depreciation, and inflation (see Griliches, 1988, Cameron, 1995a, and Cameron and Muellbauer, 1995). It is also important to adjust for the cyclical nature of the total factor productivity data (see Muellbauer, 1984).

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[12] 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 benefits of defence R&D.

[13] 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.

[14] See also Papagni (1992) on patterns of high-technology specialization across the European Union.

[15] Interestingly, Marshall and Krugman's explanations of clustering are similar to Porter's (1991) explanations of national competitive advantage.

[16] Rauch (1993), among others, applies this analysis to the formation of cities.

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

[18] Data confidentiality problems lead to the exclusion of the aerospace and photographic equipment industries from the data, and because only 3-digit data are available, the computing industry is classified within the 'electronic component's industry'.

[19] 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).

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

[21] 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).

[22] This approach is similar to that of Jaffe *et al* (1993), but using innovations rather than patents.

[23] 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. Machin (1994) presents evidence that this is likely to be a good proxy for skilled labour.

[24] See Audretsch and Stephan (1995) 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.

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[25] See Lucas (1993) for further discussion of the connection between learning rates and international trade.

[26] This analysis could apply to geographically distinct regions just as much as to politically distinct countries.

[27] Bernstein and Möhnen (1994) investigate the effect of US and Japanese R&D investment on the productivity growth and physical and R&D investment of the other country. They conclude that US R&D capital accounts for 60% of Japanese total factor productivity growth, while Japanese R&D capital contributes 20% to US productivity growth.

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

[29] See Lucas (1993) for an excellent discussion of the case of the Philippines and South Korea. Parente and Prescott (1994) argue that differences in technology across countries are due to variations in barriers to adoption.

[30] See Quah (1993a and 1993b), Durlauf and Johnson (1992), Lichtenberg (1994), and Auerbach, Hassett, and Oliner (1994) for discussion of the problems of cross-country growth regressions.

[31] Sala-i-Martin (1994) is an excellent survey of convergence issues, especially the difference between β convergence (poor countries tending to grow faster than wealthy ones) and σ convergence (the dispersion of real per capita income across countries tending to fall over time).

[32] Although potentially to different steady-states for different countries (conditional convergence).

[33] The importance of human capital in the growth process should be stressed. See Lucas (1988), Romer (1990a and 1990b) and Redding (1995) for theoretical views, and Barro (1991), O'Mahony and Wagner (1994), and Jenkins (1995) for empirical evidence.

TABLE 1

Gross Domestic Product and Augmented Joint Factor Productivity (annual average compound growth rate)

	1870-1913 GDP	1913-1950 GDP	AJFP	1950-1973 GDP	AJFP	1973-1984 GDP	AJFP
France	1.7	1.1	0.6	5.1	3.1	2.2	0.9
Germany	2.8	1.3	0.2	5.9	3.6	1.7	1.1
Japan	2.5	2.2	0.0	9.4	4.7	3.8	0.4
Netherlands	2.1	2.4	0.5	4.7	2.4	1.6	0.1
UK	1.9	1.3	0.4	3.0	1.5	1.1	0.6
USA	4.2	2.8	1.2	3.7	1.1	2.3	-0.3

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.

Source: Maddison, 1987, tables 1 and 11b.

TABLE 2

Estimates of the Output Elasticity of R&D

Study	Elasticity	Study	Elasticity
US		***France***	
Griliches (1980a)	6% f	Cuneo-Mairesse (1984)	22%-33% f
Griliches (1980b)	0%-7% i	Mairesse-Cuneo (1985)	9%-26% f
Nadiri-Bitros(1980)	26% f	Patel-Soete (1988)	13% t
Nadiri (1980a)	6%-10% p	***West Germany***	
Nadiri (1980b)	8%-19% m	Patel-Soete (1988)	21% t
Griliches (1986)	9%-11% f	***United Kingdom***	
Patel-Soete (1988)	6% t	Patel-Soete (1988)	7% t
Nadiri-Prucha (1990)	24% i	Cameron-Muellbauer (1995)	15% m
Japan		Cameron (1995b)	0%-27% i
Mansfield (1988)	42% i	***G5***	
Patel-Soete (1988)	37% t	Englander *et al* (1988)	0%-50% i
Sassenou (1988)	14%-16% f	***G7***	
Nadiri-Prucha (1990)	27% i	Coe and Helpman (1993)	23% t
		Summers-Heston Countries	
		Lichtenberg (1992)	7% t

Notes: Estimates derived from data on: f: firm level; i: industry level; t: total economy; m: total manufacturing; p: private economy.

Sources: Griliches (1991), Mairesse and Möhnen (1995), Möhnen (1990 and 1994), Nadiri (1993).

TABLE 3a

Estimates of the Rate of Return to R&D

Study	Direct Rate of Return	Indirect Rate of Return	User Matrix
US			
Minasian (1969)	54% f		
Griliches (1973)	23% t		
Terleckyj (1974)	12%-29% i	45%-78%	Intermediate Inputs
Link (1978)	19% i		
Griliches (1980a)	27% f		
Griliches (1980b)	0%-42% i		
Mansfield (1980)	28% f		
Terleckyj (1980)	0% i	183%	Intermediate Inputs
Link (1981)	0% f		
Schankerman (1981)	24%-73% f		
Sveikausas (1981)	7%-25% i	50%	Investment Goods
Scherer (1982, 1984)	29%-43% i	64%-147%	Patents
Griliches-Mairesse (1983)	19% f		
Link (1983)	0%-5% f		
Clark-Griliches (1984)	18%-20% f		
Griliches-Lichtenberg (1984a)	3%-5% i		
Griliches-Lichtenberg (1984b)	21%-76% i	41%-62%	Patents
Griliches-Mairesse (1984)	30% f		
Griliches (1986)	33%-39% f		
Griliches-Mairesse (1986)	25%-41% f		
Jaffe (1986)	25% f		
Möhnen-Nadiri-Prucha (1986)	11% i		
Schankerman-Nadiri (1986)	10%-15% f		
Wolff-Nadiri (1987)	11%-19% i	10%-90%	Intermediate Inputs
Bernstein-Nadiri (1988)	10%-27% i	11%-111%	Intermediate Inputs
Bernstein-Nadiri (1989a)	9%-20% f		
Bernstein-Nadiri (1989b)	7% f		
Griliches-Mairesse (1990)	24%-41% f		
Nadiri-Prucha (1990)	24% i		
Bernstein-Nadiri (1991)	15%-28% i	20%-110%	Intermediate Inputs
Lichtenberg-Seigel (1991)	13% f		
Bernstein-Möhnen (1994)	68% r		

Notes and Sources to Table 3a

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.

Sources: Griliches (1991), Mairesse and Möhnen (1995), Möhnen (1990 and 1994), Nadiri (1993).

TABLE 3b

More Estimates of the Rate of Return to R&D

Study	Direct Rate of Return	Indirect Rate of Return	User Matrix
Canada			
Globerman (1972)	0% i		
Hartwick-Ewen (1983)	0% i	0%	Intermediate Inputs
Postner-Wesa (1983)	0% i	18%	Intermediate Inputs
Longo (1984)	24% f		
Bernstein (1988)	12% f		
Hanel (1988)	50% i	100%	Intermediate Inputs
Möhnen-Lepine (1988)	5%-143% i	11%-314%	Intermediate Inputs
Bernstein (1989)	24%-47% i	29%-94%	Intermediate Inputs
Japan			
Odagiri (1983)	26% f		
Odagiri (1985)	(66%)-24% i	0%	Intermediate Inputs
Odagiri-Iwata (1985)	17%-20% f		
Griliches-Mairesse (1986)	20%-56% f		
Möhnen-Nadiri-Prucha (1986)	15% i		
Goto-Suzuki (1989)	26% i	80%	Intermediate Inputs+Inv.Goods
Griliches-Mairesse (1990)	20%-56% f		
Suzuki (1993)	25% f		
Bernstein-Möhnen (1994)	57% r		
France			
Griliches-Mairesse (1983)	31% f		
Hall-Mairesse(1992)	22%-34% f		
West Germany			
Bardy (1974)	92%-97% f		
Möhnen-Nadiri-Prucha (1986)	13% i		
O'Mahony-Wagner (1994)	0% i		
Belgium			
Fecher (1989)	0% f		
UK			
Möhnen-Nadiri-Prucha (1986)	11% i		
Sterlacchini (1989)	12%-20% i	19%-20%	Intermediate Inputs
Sterlacchini (1989)	12-20% i	15%-35%	Innovation Flows
O'Mahony (1992)	8% i		

O’Mahony-Wagner (1994)	0% i		
G5			
Englander *et al* (1988)	0%-50% i	0%-54%	Patents

Notes & Sources: as Table 3a.

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