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The economic benefits of publicly funded basic research: a critical review

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Abstract

This article critically reviews the literature on the economic benefits of publicly funded basic research. In that literature, three main methodological approaches have been adopted — econometric studies, surveys and case studies. Econometric studies are subject to certain methodological limitations but they suggest that the economic benefits are very substantial. These studies have also highlighted the importance of spillovers and the existence of localisation effects in research. From the literature based on surveys and on case studies, it is clear that the benefits from public investment in basic research can take a variety of forms. We classify these into six main categories, reviewing the evidence on the nature and extent of each type. The relative importance of these different forms of benefit apparently varies with scientific field, technology and industrial sector. Consequently, no simple model of the economic benefits from basic research is possible. We reconsider the rationale for government funding of basic research, arguing that the traditional ‘market failure’ justification needs to be extended to take account of these different forms of benefit from basic research. The article concludes by identifying some of the policy implications that follow from this review. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Economic benefits; Basic research; Government funding

1. Introduction

The relationship between publicly funded basic research and economic performance is an important one. Considerable government funds are spent on basic research in universities, institutes and elsewhere, yet scientists and research funding agencies constantly argue that more is needed. At the same time, governments face numerous competing demands for public funding. To many, the benefits associated with public spending on, say, health or education are more obvious than those from basic

research. However, as this article will show, there is extensive evidence that basic research does lead to considerable economic benefits, both direct and indirect. Those responsible for deciding how the limited public funds available are to be distributed (and for ensuring public accountability in relation to that expenditure) should therefore be familiar with the full range of relevant research. To this end, we review and assess the literature on the economic benefits associated with publicly funded basic research.

As we shall see, although the existing literature points to numerous benefits from publicly funded basic research, there are many flaws or gaps in the evidence. These stem from a variety of sources.

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Some are related to conceptual problems regarding the nature of basic research and how this may be changing, and the form of its outputs — whether this is information or knowledge (and whether the latter is codified or tacit), or whether other types of output such as trained people and new instrumentation are at least as important. There are also methodological issues about the approaches employed for analysing and assessing the benefits from research — for example, whether one can legitimately apply traditional economic tools such as production functions to science, or the validity of using scientific papers cited in patents as a measure of the links between science and technology. These conceptual and methodological problems point to areas where further research is needed.

In what follows, we first define the area of research covered in this study before examining in Section 3 the nature of the economic benefits of basic research and the different methodological approaches to measuring them. The next two sections then critically review and synthesise the main types of academic literature of relevance here. Section 4 deals with econometric studies on the relationship between research and productivity, the rates of return to research and ‘spillovers’. Section 5 distinguishes six main types of economic benefit from basic research and discusses empirical findings on each of these. The final section identifies the main lessons from the literature reviewed and the policy conclusions to be drawn.

2. Definitions and scope

The review is concerned primarily with *basic* research including both ‘curiosity-oriented’ research (undertaken primarily to acquire new knowledge for its own sake) and ‘strategic’ research (undertaken with some instrumental application in mind, although the precise process or product is not yet known).¹

¹ This definition should not be taken as implying a simple linear model of innovation. Basic research is just one of many inputs to technology and innovation, and new technologies or innovations, in turn, can have an impact on basic research. It should also be noted that the concept of ‘strategic’ research is very similar to the OECD category of ‘(application) oriented’ basic research.

However, much of the literature reviewed uses other terms such as ‘science’, ‘academic research’ or just ‘research’, categories that are not identical with ‘basic research’ although they overlap considerably.² We have used the terminology adopted by authors since to rephrase everything in terms of ‘basic research’ would risk distorting their arguments or conclusions. The use of an overly strict definition of what is meant by ‘basic research’ would needlessly restrict the scope of this review. Indeed, the review suggests that simple definitions of research underplay the variety and heterogeneity of the links between research and innovation. Research can have different objectives depending on the perspective of the observer. It is more appropriate to think of the different categories of research and development as overlapping activities with gradual rather than substantial differences.

The study focuses on the *economic* benefits from basic research rather than the social, environmental or cultural benefits. However, there is a fuzzy boundary between the economic and non-economic benefits; for example, if a new medical treatment improves health and reduces the days of work lost to a particular illness, are the benefits economic or social? Given this uncertainty, we define ‘economic’ quite broadly. Moreover, the study considers not only economic benefits in the form of directly useful knowledge but also other less direct economic benefits such as competencies, techniques, instruments, networks and the ability to solve complex problems. Although it may be extremely difficult to quantify these benefits with precision, this does not mean they are not real and substantial.

Lastly, the study concentrates on *publicly funded* basic research.³ This includes much of the basic

² In the United States, for example, about two-thirds of the research in universities is classified as ‘basic’, although this varies considerably across disciplines. Most analyses therefore focus on publicly funded research in general. (We are grateful to one of the referees for this point.)

³ The study’s scope was set by the UK Treasury who commissioned the work on which this article is based. It is also based on work conducted in association with David Wolfe for The Partnership Group on Science and Engineering (PAGSE) in Canada (Wolfe and Salter, 1997). We are grateful to our co-authors in these two projects.

research conducted in universities, government research institutes and hospitals. Again, however, the boundary is somewhat indistinct since some public funds go to support research that is conducted on the basis of collaboration between universities and industry. The focus on publicly funded research in this review does not imply that public research is separate or disconnected from private sector research. There is often considerable mutual interaction between public and private research activities.⁴ In many industries, as we shall demonstrate, there is a division of labour between public and private activities.

3. Conceptual and methodological overview

3.1. *The economics of publicly funded basic research*

Many of the problems in assessing the benefits of publicly funded basic research stem from limitations of the models used to evaluate those benefits. Under the traditional justification for public funding of research, government action serves to correct a ‘market failure’. The concept of market failure, rooted in neo-classical economic theory, is based on the assumption that a purely market relation would produce the optimal situation and that government policy should be limited to redressing situations where market failures have developed. As Metcalfe (1995, p. 4) notes, this is a daunting task for science policy-makers:

future markets for contingent claims in an uncertain world do not exist in any sense sufficiently for individuals to trade risks in an optimal fashion and establish prices which support the appropriate marginal conditions. Because the appropriate price structure is missing, distortions abound and the policy problem is to identify and correct those distortions. [Yet] the innovation process both generates and is influenced by uncertainty and this aspect of market failure is particularly damaging to the possibility of Pareto efficient allocation of

resources to invention and innovation... [T]hus innovation and Pareto optimality are fundamentally incompatible (ibid., p. 4).

Metcalfe offers the evolutionary approach as an alternative to justifying the case for government funding of basic research. In evolutionary theory, the focus of attention ceases to be “market failure per se and instead becomes the enhancement of competitive performance and the promotion of structural change” (ibid., p. 6).⁵ The broader perspective afforded by evolutionary theory, with its focus on both the public and private dimensions of the innovation system, appears to offer a more promising approach (Nelson, 1995).

The traditional ‘market failure’ approach to the economics of publicly funded research centres on the important role of information in economic activity. Drawing on the work of Arrow (1962), it underlines the informational properties of scientific knowledge, arguing that this knowledge is non-rival and non-excludable. Non-rival means that others can use the knowledge without detracting from the knowledge of the producers, and non-excludable means that other firms cannot be stopped from using the information. The main product from government-funded research is thus seen to be economically useful information, freely available to all firms. In this context, scientific knowledge is seen as a public good. By increasing the funds for basic research, government can expand the pool of economically useful information. This information is also assumed to be durable and costless to use. Government funding overcomes the reluctance of firms to fund their own research (to a socially optimal extent) because of their inability to appropriate all the benefits. With government funding, new economically useful information is created and the distribution of this information enhanced through the tradition of public disclosure in science.

Relatively few economists today would support the purely informational approach. Yet in certain economic writing on the relationship between publicly funded research and economic growth, there

⁴ Business-funded research also allows industry to build on their own research through absorbing and deriving benefits from other research.

⁵ For an evolutionary perspective on science and technology policy, see Lundvall (1992), Nelson (1993) and Edquist (1997).

remains a presumption of the informational properties of basic research. For example, Adams (1990) has developed a series of industry measures of the stock of knowledge by looking at articles in academic journals and the employment of scientists. He found a 20–30 year lag between scientific publication (the knowledge stock) and productivity growth. He suggested that the decline in the productivity of scientists and the subsequent fall in the stock of knowledge (measured by total papers) was related to the Second World War and speculated that 15% of the economic slowdown in the 1970s could be explained by this earlier decline in the knowledge stock (*ibid.*, p. 699).

The evolutionary approach to the economics of publicly funded research suggests that the informational view of knowledge substantially undervalues the extent to which knowledge is embodied in specific researchers and the institutional networks within which they conduct their research. It also misrepresents the nature of the innovation process, implying that scientific knowledge is “on the shelf, costlessly available to all comers” (Rosenberg, 1990, p. 165). Callon argues that scientific research is therefore not a public good because of the investment required to understand it. Scientific knowledge is not freely available to all, but only to those who have the right educational background and to members of the scientific and technological networks. The informational view fails to appreciate the extent to which scientific or technical knowledge requires a substantial capability on the part of the user. To paraphrase the OECD (1996, p. 231), knowledge and information abound, it is the *capacity* to use them in meaningful ways that is in scarce supply. Often this capacity is expensive to acquire and maintain (Pavitt, 1991, 1998). In an influential study, Cohen and Levinthal (1989) suggest that one can characterise the internal R&D efforts of firms as having two faces: their R&D both allows firms to create new knowledge and enhances their ability to assimilate and exploit external knowledge.⁶ They refer to this second dimension as the firm’s ‘absorptive capacity’.

⁶ In their paper, Cohen and Levinthal refer to “information” rather than “knowledge”. We have replaced information with knowledge here for the sake of consistency with other discussion.

The newer approach based on evolutionary economics has generated two strands of research. The first assumes that, despite the limitations of the old approach, publicly funded research can still be usefully seen as yielding information. For example, Dasgupta and David (1994) regard the informational properties of science as a powerful analytical tool for studying the payoffs to publicly funded basic research. Drawing on information theory, they suggest it is possible to develop a “new economics of science”. They focus on changes in the properties of knowledge brought about by developments in information and communication technologies such as the Internet, arguing that these allow for an expansion of the informational or codified component of scientific knowledge. They call on policy makers to focus on expanding the distributive power of the innovation system through new information resources such as electronic libraries (*ibid.*; see also David and Foray, 1995).

The second strand in the new approach focuses on the properties of knowledge not easily captured by the information view described above. Influential here are Rosenberg (1990) and Pavitt (1991, 1998), who stress that scientific and technological knowledge often remains tacit — i.e. people may know more than they can say.⁷ Moreover, the development of tacit knowledge requires an extensive learning process, being based on skills accumulated through experience and often years of effort. This perspective stresses the learning properties of individuals and organisations. Focusing on the learning capabilities generated by public investments in basic research makes it possible to apprehend the economic benefits of such investments (*ibid.*, p. 117). Of crucial importance in this approach are skills, networks of researchers and the development of new capabilities on the part of actors and institutions in the innovation system. The approach we follow here owes more to this second strand of research. The information theory approach is still quite new and has yet to be empirically validated, whereas the Rosenberg/Pavitt approach is grounded in a growing body of science

⁷ Polanyi (1962) distinguished between the two dimensions of knowledge — tacit and explicit. For an application of this concept to innovation, see Nonaka and Takeuchi (1995).

policy research and seems to offer a more productive approach to the issues under discussion.

3.2. *Methodological approaches*

In studies of the benefits of publicly funded scientific research, three main methodological approaches have been adopted: (1) econometric studies; (2) surveys; and (3) case studies. Econometric studies focus on large-scale patterns, and are effective in providing an aggregate picture of statistical regularities among countries and regions, and in estimating the rate of return to research and development. The results can, however, be misleading. Econometric approaches involve simplistic and often unrealistic assumptions about the nature of innovation. It is also very difficult to trace the benefits of the research component of a new technology through the process of innovation and commercialisation.

Surveys have opened up a productive line of research, analysing the extent to which government-funded research constitutes a source of innovative ideas for firms. Surveys have examined how different industries draw upon the supply of publicly funded research. They have helped us understand the ways in which different industries utilise the research results of different scientific fields. Surveys nevertheless suffer from several limitations. In particular, survey respondents from firms may have a bias towards the internal activities of their own companies and rather limited knowledge of their sectors and technologies.

Case studies afford the best tool to examine directly the innovation process and the historical roots of a particular technology (Freeman, 1984). They generally provide support for the main findings from econometric studies and surveys. For example, the TRACES study by the National Science Foundation showed the substantial influence of government-funded research in key innovations (NSF, 1969). However, case studies are expensive to administer, can take a long time to analyse, and yield only a narrow picture of reality.

4. Relationship between publicly funded research and economic growth

Econometricians have tried to calculate that portion of economic growth accounted for by technolog-

ical innovation in general, and by research in particular. Efforts to assess the role of technology have adopted the technique of ‘growth accounting’, analysing the contributions of production factors to economic development. Most growth models focus on the substitution of labour by capital, suggesting productivity growth occurs through the steady replacement of labour by fixed capital investments. Early growth models said little about technology, let alone the benefits of basic research. Solow and other pioneers treated technological change largely as a residual — as the portion of growth that could not be explained by labour and capital inputs (e.g. Solow, 1957, Abramowitz, 1986). Technical change was deemed to be part of the general productivity increase and played no independent role in explaining growth.

Newer models in growth theory have attempted to take account of technology more directly, with Romer’s (1990) contribution having spawned a new generation of research. Yet these models remain somewhat simplistic in their treatment of technology (Verspagen, 1993). They suggest that, by introducing a variable for ‘technical progress’, one can indirectly account for the portion of growth created by technological development. The models vary in their conclusions but all suggest a key role is played by technology in generating economic development (Lucas, 1988; Grossman and Helpman, 1991, 1994; Romer, 1994; Aghion and Howitt, 1995). However, they usually rely on simplified assumptions about the properties of information or technology, such as its durability. As yet, no reliable indicator has been developed of the benefits derived from publicly funded basic research. The models are more effective in showing that technology (however measured or treated) does play a substantial role in the growth of firms (Verspagen, 1993).

Some attempts have been made to measure the economic impact of universities or publicly funded R&D (e.g. Bergman, 1990; Martin, 1998). These studies show a large, positive contribution of academic research to economic growth. Yet, as Griliches (1995, p. 52) has stressed, the relationship between technological change and economic growth remains problematic for economic research; it is difficult to find reliable indicators of technological change and there is the econometric problem of drawing infer-

ences from non-experimental data. Furthermore, as Nelson (1982, 1998) pointed out, these models do not explain the link between publicly funded basic research and economic performance in a direct way; they simply look at inputs (such as papers) and outputs (firm sales) without analysing the process linking them. Nelson suggests that new growth theory models ought to treat technological advance as a dis-equilibrium process. In order to gain a fuller appreciation of innovation, these models should incorporate a theory of the firm, including differences across firms and in capabilities among firms. New growth models also need to take into account the role of institutions such as universities in supporting economic development (Nelson, 1998)

4.1. *Measuring the social rate of return to investments in basic research*

Studies of the rate of return to research take two forms. Some focus on the private rates of return — i.e. the return on investments in research that flow from an individual research project to the organisation directly involved. Others examine the social rates of return to research — i.e. on “the benefits which accrue to the whole society” (Smith, 1991, p. 4). The difference between the two arises because the benefits of a specific research project, or even a firm-based innovation, generally do not accrue entirely to one firm. The scientific benefit of a basic research study may be appropriated by more than one firm — for example, by imitators who replicate the new product without bearing the cost of the original research. By lowering the costs of developing new technologies or products through investing in basic research, publicly funded projects generate broader social benefits. Hence, estimates of the private rate of return to research and development tend to be much lower than those for the social rate of return. This difference underscores the importance of estimating the social rates of return for investments in scientific research, despite the severe methodological problems involved.

As Table 1 shows, estimates of private and social rates of return to privately funded R&D are large, most of them falling in the range between 20% and 50%. In a review, Hall (1993) calculated that the

Table 1
Estimates of private and social rates of return to private R&D spending

Studies	Private rate of return (%)	Social rate of return(%)
Minnasian (1962)	25	–
Nadiri (1993)	20–30	50
Mansfield (1977)	25	56
Terleckyj (1974)	27	48–78
Sveikauskas (1981)	10–23	50
Goto and Suzuki (1989)	26	80
Mohnen and Lepine (1988)	56	28
Bernstein and Nadiri (1988)	9–27	10–160
Scherer (1982, 1984)	29–43	64–147
Bernstein and Nadiri (1991)	14–28	20–110

Source: Griliches (1995, p. 72).

gross rate of return on privately funded R&D in the United States is 33%. He also suggested that the private return to R&D is not as profitable as it once was and that there may be a decline in the effect of science on productivity. However, the use of firm-level R&D spending statistics in studies such as these is a somewhat limited approach to understanding the economic benefits of investments in innovation since many firms do no formal R&D (Baldwin and Da Pont, 1996). More generally, R&D spending is only a small portion of society’s investment in activities that generate innovation. Many process innovations involve ‘grubby and pedestrian’ incremental processes within the firm and are not captured by figures for R&D (Rosenberg, 1982, p. 12). Indeed, Dennison (1985) has suggested that R&D accounts for only 20% of all technical progress. Studies that rely on R&D spending at the firm level have to be considered in the light of these limitations.

Until quite recently, few attempts had been made to measure the rates of return to publicly funded research and development. Most of these have focused on government R&D projects rather than basic research and they have not been very successful or convincing (OTA, 1986, p. 14). Nevertheless, the limited evidence gathered to date indicates that publicly funded basic research does have a large positive payoff, although this is perhaps smaller than the social rate of return on private R&D — see Table 2.

Table 2
Estimates of rates of return to publicly funded R&D

Studies	Subject	Rate of return to public R&D (%)
Griliches (1958)	Hybrid corn	20–40
Peterson (1967)	Poultry	21–25
Schmitz-Seckler (1970)	Tomato harvester	37–46
Griliches (1968)	Agricultural research	35–40
Evenson (1968)	Agricultural research	28–47
Davis (1979)	Agricultural research	37
Evenson (1979)	Agricultural research	45
Davis and Peterson (1981)	Agricultural research	37
Huffman and Evenson (1993)	Agricultural research	43–67

Source: Griliches (1995) and OTA (1986). Many authors of these studies caution about the reliability of the numerical results obtained (cf. Link, 1982).

The studies cited in Table 2 focus on relatively “successful” government R&D programmes. They assume “no alternative method could have generated the economic returns associated with the products and processes attributed to the basic research in question... [Yet] most economists would find this assumption to be an uncomfortable one, inasmuch as there are few new products and processes completely lacking substitutes” (David et al., 1992, p. 77). The costs and benefits of government-funded R&D projects need to be compared with those of alternative solutions (*ibid.*). Tracing the benefits of a particular project involves looking retrospectively at a technology, and does not take into account investments in complementary assets needed to bring the technology to market (Tece, 1986). Consequently, the resulting return on research investment may underestimate the true costs of technological development.

Using industry-level productivity growth rates as an indicator of the social rates of return to government-funded basic research is also problematic. Although studies based on this method have demonstrated a statistically significant impact for government-funded basic research on productivity growth at the sectoral level, most have been at a high degree of aggregation, rarely controlling for inter-industry differences. “Moreover, they do not reveal how the economic returns of basic research (and development) are [actually] realised” (David et al., 1992, p.

79). Other econometric studies have reached intriguing conclusions. For example, Hall (1993) showed that one impact of publicly funded basic research may be to increase a firm’s own R&D spending (cf. Cohen and Levinthal, 1989).

Despite the above problems, Mansfield made substantial progress in measuring the benefits of basic research. He focused on ‘recent’ academic research — i.e. research within 15 years of the innovation under consideration (Mansfield, 1991). Using a sample of 76 US firms in seven industries, he obtained estimates from company R&D managers about what proportion of the firm’s products and processes over a 10-year period could not have been developed without the academic research. He found that 11% of new products and 9% of new processes could not have been developed without a substantial delay in the absence of the academic research, these accounting for 3% and 1% of sales, respectively. He also measured those products and processes developed with ‘substantial aid’ from academic research over the previous 15 years; 2.1% of sales for new products and 1.6% of new processes would have been lost in the absence of the academic research. Using these figures, Mansfield estimated the rate of return from academic research to be 28% (*ibid.*, p. 10).

In 1998, Mansfield published the results of a follow-up study. He found that academic work was becoming increasingly important for industrial activities. On the basis of a second survey of 70 firms, Mansfield estimated that 15% of new products and 11% of new processes could not have been developed (without a substantial delay) in the absence of academic research. In total, innovations that could not have developed without academic research accounted for 5% of total sales for the firms. Mansfield’s second study also suggests that the time delay from academic research to industrial practice has shortened from 7 years to 6. Mansfield made no attempt in this paper, however, to estimate a rate of return to academic research. He suggested that increasing links between academic research and industrial practice may be a result of a shift of academic work toward more applied and short-term work and of growing efforts by universities to work more closely with industry.

Mansfield recognised the limitations of his approach: the time lag (15 years) is short; it is assumed

that no benefits accrue to firms outside the US and that there are no indirect benefits from research, such as skilled researchers; the estimates rely on the opinions of managers in large firms; and they do not consider the full costs of commercialisation (CBO, 1993, p. 15). Moreover, the approach yields only the average rate of return, not the marginal rate, so it cannot inform policy makers about the marginal benefits of additional research funding (OTA, 1986, p. 4; David et al., 1992, p. 79).⁸ Mansfield's figures are also hard to compare with other data on rates of return on investments. If the benefits are so great, why do governments and firms not invest more in research? The lack of investment might be related to the riskiness of R&D. If so, these estimates cannot be compared directly with other figures on rates of return (e.g. on capital equipment).

Beise and Stahl (1999) have replicated Mansfield's survey in Germany with a much larger sample of 2300 manufacturing firms. They found that approximately 5% of new product sales could not have developed without academic research. They also showed that academic research has a greater impact on new products than new processes and that small firms are less likely to draw from universities than large firms (*ibid.*, p. 409). This study shares many of the difficulties of Mansfield's early study and, unlike Mansfield, does not take into account sectoral differences in the importance of academic research to industrial innovation.

Narin et al. (1997) have developed a new approach to evaluating the benefits of publicly funded research based on analysing scientific publications cited in US patents. Examining the front pages of 400,000 US patents issued in 1987–1994, they traced the 430,000 non-patent citations contained in these patents, of which 175,000 were to papers published in the 4000 journals covered by the Science Citation

Index (SCI). For 42,000 papers with at least one US author, they determined the sources of US and foreign research support acknowledged in the papers. Their findings on the increasing number of scientific references cited in patents suggest that over a period of 6 years there has been a tripling in the knowledge flow from US science to US industry. US government agencies were frequently listed as sources of funding for the research cited in the patents. Narin et al. suggest that this indicates a strong reliance by US industry on the results from publicly funded research (*ibid.*).

One possible methodological limitation of this work is that it focuses on the citations to the scientific literature made by the patent examiner rather than those made by the applicant. The three-fold increase of scientific citations in US patents may partly reflect a policy at the US Patent Office⁹ to promote scientific citations, changes in patent law, or simply the availability of relevant data from new CD-ROMs listing academic papers by subject. It seems surprising that there could have been such a dramatic shift in the relationship between US industry and science over a period of just 6 years.

As noted by David et al. (1992), measuring the economic benefits to basic research is complicated by industry differences. A summary table developed by Marsili (1999) illustrates the patterns within and differences across industries in the relationship between academic research and industrial innovation. Table 3 is based on a statistical analysis of the Pace survey of European industrial managers (Arundel et al., 1995), US R&D data, employment patterns in different industries, and patent citations.¹⁰ Using the Pace survey, Marsili classified industries in terms of the contribution of academic research to innovation in each sector from very high to low. The underlying scientific knowledge that industries draw upon in their innovation activities was also described using Pace survey data.

⁸ In a review of Mansfield's work, the Congressional Budget Office noted that his findings could not guide policy makers on the allocation of funds nor be used to determine the amount of funding to devote to R&D (CBO, 1993). This did not stop the Bush Administration from citing Mansfield's work as a justification for an increase in basic research funding.

⁹ Patents issued by the European Patent Office do not apparently exhibit the same dramatic increase in the number of scientific references.

¹⁰ A similar table is produced in Godin (1996).

Table 3
The role of academic research in different industries

Contribution of academic research	Development activities engineering disciplines (mainly tacit)	Research-based activities basic and applied science (mainly codified)
Very high	Computers	Pharmaceuticals
High	Aerospace	Petroleum
	Motor vehicles	Chemicals
	Telecommunications and electronics	Food
	Electrical equipment	
Medium	Instruments	Basic metals
	Non electrical machinery	Building materials
Low	Metal products	Textiles
	Rubber and plastic products	Paper
Relevant scientific fields ^a	Mathematics, computer science, mechanical and electrical engineering	Biology, chemistry, chemical engineering

Source: adapted from Marsili (1999).

^aPhysics is important for both research and development activities. In the statistical analysis, physics was not highly significant in discriminating between the two groups and therefore it has not been included in the table.

Using US R&D data, Marsili estimated the percentage of research undertaken in each industry which is basic, applied and development in orientation. These results were compared with data on employment patterns of technical personnel (e.g. scientists, engineers and technicians) across different industries. As one might expect, the distribution of R&D is correlated with the distribution of employment — for example, industries with high levels of basic research employ large numbers of scientists. Marsili (1999) also analysed the degree of codification in the knowledge base of each industry, using the number of academic papers cited in patents as a measure of that codification (cf. Narin et al., 1997). The results indicate that firms and industries draw from publicly funded science in a heterogeneous fashion. In some sectors, the link is quite direct, with numerous citations to scientific papers in patents and a close interest in scientific research. In other sectors, such as automobiles, firms draw from the public base more indirectly, mostly through the flow of students who help the firm overcome technological challenges. These differences in the ways in which individual sectors derive their benefits suggest that any attempt at a simple calculus of the benefits of government-funded basic research is likely to be misleading.

As Meyer-Krahmer and Schmoch (1998, p.837) suggest, “a weak science linkage of a technology does not imply low university–industry interaction”.

Using a combination of European Patent Office data and a survey of universities on their linkages with industry, they show that there is a “two-way” interaction between universities and industry. Collaborative research and informal contacts are the most important forms of interaction between universities and industry. Academic researchers gain funding, knowledge and flexibility through industrial funding. Collaborative research between universities and industry almost always involves a two-directional flow of knowledge and informal discussion is preferred to publications for contacts. The strength of university–industrial interactions is dependent on the ‘absorptive capacity’ of the industry and the innovation system (ibid.; see also Schmoch, 1997). Meyer-Krahmer and Schmoch’s findings show that it is almost impossible to measure the extent to which a sector like automobiles gains economic benefits from the publicly funded research infrastructure. Only in pharmaceuticals, where the links are direct and often visible, might some measurement of the benefits be feasible.

4.2. *Spillovers and localisation*

One prominent line of recent research into the benefits of publicly funded research has been the investigation of the spillovers from government funding to other activities such as industrial R&D. The existence of these spillovers augments the pro-

ductivity of a firm or industry by expanding the general pool of knowledge available to it. Two main forms of spillover have been identified: (1) geographical spillovers and (2) spillovers across sectors and industries (Griliches, 1995). The former imply benefits for firms located near research centres, other firms and universities. Evidence from bibliometric studies indicates a strong tendency for basic research to be localised. Katz (1994) has shown that research collaboration within a country is strongly influenced by geographical proximity; as distance increases, collaboration decreases, suggesting that research collaboration often demands face-to-face interaction. Hicks et al. (1996) also found that research across countries is localised.

Jaffe has attempted to measure geographical spillovers in the US employing a three-equation model (involving patenting, industrial R&D and university research). Using patents as a proxy for innovative output, he examined the relationship between patents assigned to corporations in 29 US states in 1972–1977, 1979 and 1981, industrial R&D and university research. His results demonstrate that there are spillovers from university research and industrial patenting. There is also an association between industrial R&D and university research at the state level. It appears that university research encourages industrial R&D, but not vice versa (Jaffe, 1989). In a similar study, Acs et al. (1991) found that the spillovers between university research and innovation are greater than Jaffe described.¹¹ Anselin et al. (1997) also observed significant spillovers from university research and ‘high technology’ innovations at the level of metropolitan units or cities. Feldmann and Florida (1994) developed a four-variable model (based on distribution of university research, industrial R&D expenditures, distribution of manufacturing, and distribution of producer services) to test for

geographical effects. Using the same data as Acs, they showed that geography does matter in the process of innovation, with the variables being highly correlated.¹² These findings are supported by the work of Mansfield and Lee (1996) who found that firms close to major centres of academic research have a major advantage over those located at a distance.¹³

While economists and others sometimes assume that new knowledge is a public good that quickly and cheaply becomes available to all, this is far from true. According to executives from our sample [of 70 major US companies], firms located in the nation and area where academic research occurs are significantly more likely than distant firms to have an opportunity to be among the first to apply the findings of this research (*ibid.*, p. 1057).

Similarly, Hicks and Olivastro (1998) have shown that US company patents tend to cite papers produced by local public-sector institutions, with over 27% of ‘state-of-the-art’ references in patents being to institutions within the US state in which the patent was taken out. They suggest that “papers and patents . . . were written precisely to make explicit . . . complex, tacit knowledge” (*ibid.*, p. 4). There is also evidence for geographical effects at the national level, with Narin et al. (1997) finding national patterns in the public research cited in industrial patents. For example, patents taken out by German firms in the US are 2.4 times more likely to cite German public scientists among their scientific references than other nationalities, and similar results are obtained for other major countries.

However, these geographical effects are not necessarily universal. Beise and Stahl (1999) found that, while firms in Germany tend to cite local public

¹¹ Acs et al. used a database of innovations prepared by the US Small Business Administration in 1982. The database contains innovations reported in the literature for one year (1982) broken down by city and state. Such databases are inherently subjective, relying on innovations cited in technical journals. The database focuses on a limited number of product innovations for a single year. The date of the database collection also raises questions about the reliability of the findings given the changes in the economy over the past 17 years.

¹² “In the modern economy, locational advantage in the capacity to innovate is ever more dependent on the agglomerations of specialised skills, knowledge, institutions, and resources that make up the underlying technological infrastructure (of a place)” (Feldmann and Florida, 1994, p. 12).

¹³ Among the limitations of this study are that it was based on a relatively narrow sample of firms and that it only asked industrialists to list the five most important academics for their firm’s activities.

institutions, especially polytechnics, there were no significant differences between firms with innovations drawing upon public research and all other firms in the distribution of distances of academic scientists cited by the firms they surveyed. They suggest that this finding indicates that it is “hard to believe that closeness to research institutions has an effect on the probability of public research-based innovations” (*ibid.*, p. 411).¹⁴ More important than distance, they argue, is the willingness of firms to invest in in-house R&D. For polytechnics and small firms distance still matters, but for large firms and universities distance appears to be much less important.

Recent work in economic geography also stresses the importance of geographical agglomerations and spillovers. Saxenian’s (1994) study of Silicon Valley and Route 128 concluded that local institutions (including the research infrastructure) profoundly shape a region’s capacity to innovate. Storper (1995, 1997) suggested that the development of geographical agglomerations is a result of the person-embodied nature of much technological knowledge and the consequent importance of face-to-face interactions. Since these personal interactions are essential to deal with the uncertainty inherent in the future development of technologies or markets, firms and individuals tend to cluster. Their interactions are often untraded and this helps to create a social environment that allows and indeed encourages individuals to share knowledge and ideas. The consequent interdependencies are place-specific and context-dependent, resulting from continuous interactions among firms and individuals as they go about developing technology and solving common problems (Dosi et al., 1988; Storper, 1995, 1997; Cooke and Morgan, 1998).

The value of geographic spillovers and untraded interdependencies varies over time. They may be particularly important when the technological trajectories (Dosi, 1982) are highly indeterminate — in other words, when a wide range of possible paths of development increases the importance of tacit

knowledge to the innovation process, thus raising the value of direct interactions in interpreting and applying new information. These untraded interdependencies form the collective property of the region and help the regional actors expand their range of activities, drawing one another forward (*cf.* Lundvall, 1988). All this suggests that each nation or region needs to maintain its own capability in research and development. Personal links and face-to-face interactions are essential not only for the research process but also for sharing and transferring knowledge quickly and effectively. Policies designed to support geographical agglomeration should help facilitate this interaction (Wolfe, 1996).

Spillovers are also common among research-related activities: “the level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the general pool of knowledge accessible to it” (Griliches, 1995, p. 63). Using US patent data, Scherer (1982) constructed development measures of the direction of spillovers by classifying a large sample of patents in terms of the industry where the innovation occurred and of the industry where it was expected to have an impact. Los and Verspagen (1996) have expanded the treatment of spillovers, looking at the locational origin of patents and papers cited in US patents to determine the degree of spillover of domestic sources of science and technology. They found that spillovers do exist but they vary across sectors and countries.¹⁵

Work by economists on new growth theory highlights the spillover effects of technological development. Indeed, growth theorists tend to see spillovers as the main mechanism underlying growth patterns (Romer, 1994, Grossman and Helpman, 1994).¹⁶ These models suggest that the encouragement of spillovers through government institutions may be fruitful from a policy perspective (Romer, 1990).

¹⁵ Los and Verspagen’s approach faces similar methodological problems to that of Narin et al. (1997).

¹⁶ The case for spillovers is strong but needs to be tempered by an understanding of the importance of firm-level dynamics. As Rosenberg (1990) has emphasised, technological development takes place within the firm; external relations among firms, such as spillovers, help to constitute these internal firm dynamics.

¹⁴ Some of these differences in findings are probably linked to the considerable geographical differences between Europe and the United States. (We are grateful to a referee for pointing this out.)

These models do, however, rely largely on the theoretical elaboration of production functions and make limited use of empirical data. Most models also focus on industrial R&D rather than publicly funded basic research. These models show that knowledge and technologies spill over across sectors and fields but it is difficult to develop useful measures of the extent of these spillovers. Often the links between government-funded basic research and production are varied and indirect. Simple measures such as sales or cross-patent citations only capture these spillovers to a limited degree.

5. The main types of benefit from publicly funded research

Despite the methodological problems discussed above in estimating the economic returns to public investment in basic research, one can distinguish various types of contributions that publicly funded research makes to economic growth (Martin et al., 1996):

1. increasing the stock of useful knowledge;
2. training skilled graduates;
3. creating new scientific instrumentation and methodologies;
4. forming networks and stimulating social interaction;
5. increasing the capacity for scientific and technological problem-solving;
6. creating new firms.

Although these six categories of benefits are clearly interrelated and overlap,¹⁷ it is useful to separate them analytically. In what follows, we draw upon recent science policy research to analyse the

¹⁷ For example, the category of ‘increasing the capacity for scientific and technological problem-solving’ is obviously quite closely related to that of ‘training skilled graduates’. However, we have chosen to separate them analytically here partly because the two categories are not identical (problem-solving may also draw upon knowledge, methodologies and networks, for example) and partly because of the emphasis given to the problem-solving component by industrialists when surveyed about the benefits of basic research.

benefits that flow from government funding of basic research in each category. It should be emphasised that these six types of benefits are not limited to publicly funded basic research; privately funded basic research can yield similar benefits.

5.1. Increasing the stock of knowledge

The traditional justification for public funding of basic research is that it expands the scientific information available for firms to draw upon in their technological activities. However, this underplays the substantial efforts (and associated costs) required from users to exploit such information. The difficulty with the information theory of basic research is that the commercial value of scientific findings is not always immediately evident. An authoritative review (OTA, 1995, p. 43) noted numerous examples of scientific advances whose commercial application could not fully be conceived of at the time of their discovery (e.g. lasers). Yet, despite the difficulties in tracing the path from scientific discovery to practical application, firms apparently rely quite heavily on publicly funded research as a source of new ideas or technological knowledge (Narin et al., 1997). Public and private research systems tend to complement each other. The two systems are interlinked by common interests, institutional affiliations and personal connections. As Meyer-Krahmer and Schmoch (1998) suggest, there is ‘two-way interaction’ between public and private knowledge generation and diffusion.

Nelson and Rosenberg (1994, p. 341) argue that publicly funded basic research often stimulates and enhances the power of R&D done in industry, rather than providing a substitute for it. Klevorick et al. (1995) suggest that one can think of government funding for basic research as expanding the technological opportunities available to society. They use the analogy of firms drawing balls from an urn in the process of technological development. Government funding for scientific research adds more balls to the urn, thus increasing the chances for firms to draw out a winner. Mowery (1995, p. 521) argues that the informational outputs of basic research can “offer rules for empirical generalisation from specific indications that can improve the efficiency of technology

development” (see also Dasgupta and David, 1994). Steinmueller (1994, p. 59) suggests that scientific knowledge may affect the ‘options value’ of applied development by “reducing the expected returns of some lines of applied research... or increasing the real returns in other areas”.

Much confusion exists in the literature over what it is that firms draw from public sources — ‘information’ or ‘knowledge’. In many innovation surveys, these terms are used interchangeably and for most firms the distinction between the two is somewhat academic. However, the difference is important for understanding the role played by basic research. The traditional justification for government-funded basic research relies on the ‘public good’ qualities of information. Yet the evidence from science policy studies indicates that what firms draw upon is not information but knowledge. To understand information almost always requires knowledge. Individuals and organisations need a complex set of skills and must expend significant resources to absorb and understand information. Without these investments, firms would be unable to use the information available. Information only becomes knowledge (and therefore valuable) when users have the capabilities to make sense of it; without these, information is meaningless (Nightingale, 1997; Pavitt, 1998).

Here, it important to distinguish between codified and tacit knowledge. Faulkner and Senker (1995) argue that codified knowledge on its own is capable of providing only limited information since the application of such knowledge requires other tacit knowledge and more personal interaction. A related finding is that of Hicks and Katz (1997) who have shown that firms are publishing an increasing num-

ber of scientific journal articles, apparently undermining the informational view of economic benefits according to which firms should be reluctant to codify their knowledge for appropriability reasons. Hicks (1995) suggests that firms use their published papers not only to present codified knowledge but also to signal to others the presence of tacit knowledge and expertise. Likewise, publications by others can be interpreted as an indication of the existence of relevant tacit knowledge (Godin, 1996).

The Pace survey (Arundel et al., 1995) of large European firms in 16 industrial sectors shows that publications remain the most common source for companies to learn about public research — see Table 4. This and other evidence on the ways firms use publicly available knowledge stocks suggests that government funding provides an important means for expanding the technological opportunities open to firms. At the same time, firms must invest substantial resources in acquiring and using this information since publications on their own rarely contain economically useful information. Government funding for science, to the extent that it leads to publications, therefore helps to identify relevant tacit knowledge. Open publication is consequently an essential aspect of publicly funded science. Publications expand the opportunities for firms to access the knowledge and skills base in the scientific community created by public investment in basic research (Dasgupta and David, 1994).

This argument differs from the old information-based view of the benefits of publicly funded research. Firms use publications to network, to develop contacts and to signal expertise. Codified and tacit knowledge are inextricably linked (Hicks, 1995).

Table 4
Importance of different sources for learning about public research

Source	% rating as important	High scoring industries (scores in percentages)
Publications	58	Pharmaceuticals (90), basic metals (64), GCC (62), utilities (61)
Informal contacts	52	Pharmaceuticals (88), GCC (68), utilities (67), aerospace (60)
Hiring	44	Pharmaceuticals (85), computers (56), aerospace (52), chemical (48)
Conferences	44	Pharmaceuticals (85), utilities (56), computers (56), telecom (48)
Joint research	40	Aerospace (70), basic metals (68), utilities (67), pharmaceuticals (51)
Contract research	36	Utilities (72), pharmaceuticals (51), basic metals (48), plastics (46)
Temporary exchanges	14	Pharmaceuticals (27), computers (22), electrical (20), basic metals (20)

Source: Arundel et al. (1995). 640 respondents rated the importance of each source on a 7-point scale. The figures indicate the percentage of respondents rating each source 5 or higher on that scale.

Accessing and using codified knowledge are costly, time-consuming and difficult, yet frequently hold the key to the development of innovations by the firm. The publications resulting from government-funded research make these processes easier.

5.2. *Skilled graduates*

Many studies of the economic benefits of publicly funded research identify skilled graduates as the primary benefit that flows to firms. New graduates entering industry bring not only a knowledge of recent scientific research but also an ability to solve complex problems, perform research and develop ideas. The skills developed during their education with advanced instrumentation and techniques may be especially valuable. Gibbons and Johnston (1974), in their analysis of the role of science in technological innovation, pointed to trained students as a key benefit from research funding. Martin and Irvine (1981) showed that even students from very basic fields such as astronomy may move into industry and make major contributions. Nelson (1987) noted that academics may teach what industrial actors need to know without necessarily doing ‘relevant’ research for industry. For example, basic research techniques are often essential for young scientists to learn to participate in the industrial activities within the firm. As Senker (1995) pointed out, graduates bring to industry an ‘attitude of the mind’ and a ‘tacit ability’ to acquire and use knowledge in new and powerful ways.

Even in applied areas of science and engineering, however, the transfer of students into industry is rarely a smooth process. Often firms have to make large investments in training new graduates. Students may come prepared to learn but they need to be taught industrial practice before they can be used by firms to expand their technological competencies. Yet recent graduates bring both enthusiasm and a critical approach that stimulates others and raises standards. Moreover, the skills acquired during education are often a necessary precursor to the development of more industry-specific skills and knowledge.

Since graduates provide a key mechanism for the benefits of public funding to be transferred to industry, it is vital that government-funded basic research and student training are conducted in the same insti-

tution. There are also some benefits to be derived from training students in research institutes engaged in industry-related research (Gibbons et al., 1994). Such students gain practical experience of firms’ needs and competencies. At the same time, one has to strike a balance between developing an understanding of industrial practice and providing an education that equips students with more generic and long-lasting skills.

5.3. *New instrumentation and methodologies*

Historical research (e.g. Rosenberg, 1992) has shown that the development of new instrumentation and methodologies is a key output of government-funded basic research. However, few attempts have been made to evaluate this form of benefit. In particular, innovation surveys rarely consider instrumentation because of the limited ability of industrial R&D managers to recognise the contribution made by earlier government-funded research.

The challenges involved in basic research continually force researchers to design new equipment, laboratory techniques and analytical methods to tackle specific research problems. Some of these may eventually be adopted in industry. Examples include electron diffraction, the scanning electron microscope, ion implantation, synchrotron radiation sources, phase-shifted lithography, and superconducting magnets (OTA, 1995, p. 38). As Rosenberg (1992) has noted, scientific instruments have become almost indistinguishable from industrial capital goods in many industries such as semiconductors: “Indeed much, perhaps most, of the equipment that one sees today in an up-to-date electronics manufacturing plant had its origin in the university research laboratory” (ibid., p. 384).

There are strong feedbacks between instruments developed in the course of research and those developed by firms (Von Hippel, 1987; Schrader, 1991). Not only is new instrumentation drawn upon by firms as scientists take advantage of the new tools to expand their research; often the introduction of new instrumentation can then lead to the development of a new field of research such as computational physics or artificial intelligence. Rosenberg (1992) argues that such instrumentation would generally not have

been developed without government funding allowing researchers to probe fundamental questions.

Work by Nelson et al. (1996) on the licensing of technologies at Columbia University indicates that firms tend to license mainly research tools and techniques from the university — in other words, much of the ‘technological output’ of the university system apparently lies in instrumentation and techniques (cf. Rosenberg, 1992). Likewise, the Pace Report (Arundel et al., 1995) shows that firms rate instrumentation as the second most important output of public research, particularly firms in the pharmaceuticals, glass, ceramics and cement, electrical and aerospace industries — see Table 5.

5.4. Networks and social interaction

De Solla Price (1984) was one of the earliest to identify the role of government-funded research in providing an entry point into networks of expertise and practice. Government funding affords individuals and organisations the means to participate in the world-wide community of research and technological development. The economic benefits of such networks are difficult to measure. Nevertheless, the evidence (e.g. in Table 4) suggests that firms do find informal methods of interaction an important means of learning about public research and technological activity.

Networks have been the focus of much empirical research. This work indicates that firms and industries link with the publicly funded science base in many different ways and these links are often informal. Faulkner and Senker (1995) studied public–private sector linkages in biotechnology, engineering ceramics and parallel computing. Good personal rela-

tionships between firms and public-sector scientists emerged as the key to successful collaboration between the public and private sectors. Personal relations develop the understanding and trust on which long-term contractual relationships can then be built. Networks may also provide access to sophisticated instrumentation and equipment for small firms.

Rappa and Debackere (1992) suggested that there are technological communities in which loosely coupled individuals converge toward a common goal. Using a survey of the neural network community, they showed that, although academics are more willing to publish their findings and communicate new discoveries in general, industrial actors also seek an exchange of ideas within their technological communities (*ibid.*). In other words, industrial actors are embedded in strong and often informal technological communities drawing on network relations with academic researchers as they develop new products and processes.

Callon (1994) has suggested that government funding for basic research should be seen as a means of establishing new networks. Funding stimulates new combinations of relations between organisations and individuals, creating new forms of interaction. The market, by contrast, tends to “use up” the existing sources of variety, leading to convergence and irreversibility and locking society into particular technological options. Government action is required to break this cycle, to create new options and thereby to counter these market tendencies to exhaust the existing stock of ideas and relations. Through government funding, it is possible to create novel approaches to addressing and resolving technical problems by increasing the variety of scientific options available to firms. In short, government funding

Table 5
Importance to industry of different outputs of public research

Form of output	% rating as important	High scoring industries (scores in percentages)
Specialised knowledge	56	Pharmaceuticals (84), utilities (64), food (57), aerospace (57)
Instrumentation	35	Pharmaceuticals (49), GCC (45), electrical (42), aerospace (39)
General knowledge from basic research	32	Pharmaceuticals (76), chemical (38), computers (38), instruments (36)
Prototypes	19	Food (28), pharmaceutical (27), electrical (26), basic metals (24)

Source: Arundel et al. (1995). Respondents rated the importance of each output on a 7-point scale. The figures indicate the percentage of respondents rating each output 5 or higher.

expands social interaction, creating new links between social actors; those links then add to the pool of technological opportunities available to firms (*ibid.*).

Lundvall (1992) has also stressed the need for government funding to generate new forms of interactions among actors in the national innovation system. He suggests that the interactive nature of the learning process that characterises innovation requires support from institutions which facilitate contact between actors within the system. Increasingly, knowledge and intelligence are organised in social ways, rather than being accessed on an individual basis. The capacity for networking is essential for

tapping into the intelligence of others. The network model recognises the growing relevance of the tacit dimension of knowledge and the extent to which this is often grounded in the informal sharing of knowledge and ideas among firms and other relevant institutions such as universities. The very density of these networks and the links that comprise them is perhaps an indicator of the vibrancy of a regional or national economy (Cooke and Morgan, 1993, p. 562).

5.5. *Technological problem-solving*

Publicly funded research also contributes to the economy by helping industry and others to solve

Table 6
Relevance of university research and knowledge of science to technology

Scientific field	No. of industries rating university research as important and high scoring industries		No. of industries rating knowledge of science as important and high scoring industries	
Biology	12	Animal feed, drugs, processed food	14	Drugs, pesticides, meat products, animal feed
Chemistry	19	Animal feed, meat products, drugs	74	Pesticides, fertilisers, glass, plastics
Geology	0		4	Fertilisers, pottery, non-ferrous metals
Mathematics	5	Optical instruments	30	Optical instruments, machine tools, motor vehicles
Physics	4	Optical instruments, electron tubes	44	Semiconductors, computers, guided missiles
Agricultural science	17	Pesticides, animal feed, fertilisers, food prod.	16	Pesticides, animal feed, fertilisers, food prod.
Applied math/O.R.	16	Meat products, logging/sawmills	32	Guided missiles, aluminium smelting, motor vehicles
Computer science	34	Optical instruments, logging/sawmills	79	Guided missiles, semiconductors, motor vehicles
Materials science	29	Synthetic rubber, non-ferrous metals	99	Primary metals, ball bearings, aircraft engines
Medical science	7	Surgical/medical instruments, drugs, coffee	8	Asbestos, drugs, surgical/medical instruments
Metallurgy	21	Non-ferrous metals, fabricated metal products	60	Primary metals, aircraft engines, ball bearings
Chemical engineering	19	Canned foods, fertilisers, malt beverages		N/A
Electrical engineering	22	Semiconductors, scientific instruments		N/A
Mechanical engineering	28	Hand tools, specialised industrial machinery		N/A

Source: Klevorick et al. (1995). Respondents rated the importance of each scientific field on a 7-point scale. The figures indicate the number of industries (out of a total of 130) rating each field 5 or more on the scale.

complex problems. Many firms in technologically demanding industries need to combine a variety of technologies in complex ways, and publicly supported research provides an extensive pool of resources from which these firms may draw (Patel and Pavitt, 1995). Vincenti's (1990) analysis suggests that advanced engineering benefits indirectly from the publicly supported research base through the provision of trained problem-solvers as well as the background supply of knowledge. Pertinent here is the Yale survey of 650 R&D directors in large US firms that provides one of the most systematic analyses of the benefits of basic research. The authors distinguished between the role of science in providing a general pool of knowledge and the role of specific university research for firms. The former was judged to be important to recent technological advance by approximately three times as many respondents as the latter — see Table 6.

The discrepancy between the measured relevance of generic science (a pool of knowledge) and that of university science (new results) is greater for basic than for applied research because research in applied sciences and engineering disciplines is guided to a large extent by perceptions of practical problems, and new findings often feed directly into their solutions... [T]his by no means implies that new findings in fundamental physics, for example, are not relevant to industrial innovation.

Rather, we read our findings as indicating that advances in fundamental scientific knowledge have their influence on industrial R&D largely through two routes. One... is through influencing the general understandings and techniques that industrial scientists and engineers, particularly those whose industrial training is recent, bring to their jobs. The other is through their incorporation in the applied sciences and engineering disciplines and their influence on research in those fields' (Klevorick et al., 1995, pp. 196–97).

The Pace survey of European companies confirms these conclusions although the links between industries and sciences vary by sector and country. As in the Yale study, respondents were asked to rate different fields of science in terms of their importance to their firms' technological base. Applied areas of research received fairly high scores as did chemistry, while physics, biology and mathematics were judged less important — see Table 7.

Nelson and Rosenberg (1994) argue that the low scores accorded in innovation surveys to fundamental sciences such as physics do not necessarily imply that these fields fail to provide benefits to industry. They suggest that insights from basic research often trickle down to industry via engineering schools, which draw upon fundamental sciences to develop technical knowledge for engineering and design. There is a strong feedback between engineering

Table 7
Importance to technology base of publicly funded research in past 10 years

Scientific field	% of respondents rating as important	High scoring industries (scores in percentages)
Material sciences	47	Aerospace (77), basic metals (76), electrical (72), GCC (63)
Computer sciences	34	Aerospace (60), telecom (56), automotive (47), computers (47)
Mechanical engineering	34	Automotive (64), aerospace (64), utilities (53), computers (47)
Electrical engineering	33	Computers (78), aerospace (73), telecom (70), electrical (56)
Chemistry	29	Pharmaceuticals (78), petroleum (52), chemical (46), computers (33)
Chemical engineering	29	Petroleum (60), pharmaceuticals (55), chemical (46), plastics (42)
Physics	19	Computers (64), basic metals (33), plastics (25), GCC (25)
Biology	18	Pharmaceuticals (71), food (33), petroleum (18), chemical (17)
Medical	15	Pharmaceuticals (85), instruments (29), computers (27), food (15)
Mathematics	9	Computers (25), aerospace (20), automotive (20), GCC (13)

Source: Arundel et al. (1995). Respondents in 16 industries rated the importance of publicly funded research on a 7-point scale. The figures indicate the percentage of respondents rating publicly funded research 5 or higher.

knowledge and fundamental science; for example, knowledge about electrical engineering often depends on fundamental discoveries in physics or mathematics (*ibid.*, p. 342).

5.6. *Creation of new firms*

The creation of new firms is sometimes cited as a benefit of government-funded research. However, the evidence is mixed as to whether new firms have been established on a significant scale as result of government funding. There are certainly some spectacular examples of regional agglomerations of new firms clustered around research-intensive universities such as MIT and Stanford. Yet a review of several studies found little convincing evidence that significant investment in basic research generates spin-off companies; while the correlation between university research and firm birth¹⁸ is positive and statistically significant in the electronic equipment sector, in other sectors it is statistically insignificant (Bania et al., 1993). New firm growth is not, however, the only issue. Often the companies created by spin-offs remain quite small and have a high failure rate (for example, in the software sector). Such companies can provide an important source of Schumpeterian clustering around a new technology, but simple head counts of numbers of new firms can be misleading. Firm entry and exit rates vary considerably between sectors and regions. Moreover, many of the firms which are ‘spun out’ of universities have low growth rates (Massey et al., 1992). Studies of firms located in science parks indicate that a connection to a university can be advantageous for new small firms, but this advantage is often quite limited (Storey and Tether, 1998). Successful and sustained innovation involves more than the development of an idea. As Stankiewicz (1994, p. 101) has noted, “Academics do not make good entrepreneurs and the effective exploitation of their technology usually requires that the ownership of the technology and the managerial control are taken out of their hands at an early stage”.

¹⁸ The study ignored firm deaths.

6. Conclusions

6.1. *Findings*

In this study, we have critically reviewed the literature on the economic benefits of publicly funded research. As we have seen, this literature falls into three main categories. One consists of econometric studies, where there have been numerous attempts to estimate the impact of research (in general) on productivity. Virtually all have found a positive rate of return, and in most cases the figure has been comparatively high. However, these attempts have been beset with both measurement difficulties and conceptual problems such as the assumption of a simple production function model of the science system. In particular, they tend to assume that research is, first and foremost, a source of useful information to be drawn upon in the development of new technologies, products and processes. This ignores the other forms of economic benefit discussed in Section 5.

As regards the specific case of *basic* research, one can try to estimate the rate of return but only on the basis of very questionable assumptions. Mansfield’s work suggests there is a very substantial rate of return, but the precise figure he arrives at (28%) is open to some doubt. Among the problems are (i) the complementary linkages of basic research activities with much larger ‘downstream’ investments in development, production, marketing and diffusion; and (ii) the complex and often indirect contributions of basic research to technology, the balance of which varies greatly across scientific fields and industrial sectors. Recent work by Narin et al. (1997) based on the scientific papers cited in patents provides a tool for mapping these linkages and suggests that the knowledge flow from US science to US industry is substantial and growing rapidly, although this finding is again subject to certain methodological reservations.

The econometric literature on localisation effects and spillovers emphasises that advanced industrial countries need their own, well developed basic research capabilities in order to appropriate the knowledge generated by others and to sustain technological development. Personal links and mobility are vital in integrating basic research with technological development. This, in turn, highlights the importance of

linking basic research to graduate training, a point to which we return later.

Surveys and case studies of different forms of economic benefit from basic research represent the two other types of literature reviewed here, and these have yielded a number of findings. One concerns the traditional justification for the public funding of basic research which is based on the argument that science is a public good, with the emphasis being on the role of basic research as a source of new useful knowledge, especially in a codified form. However, numerous studies have shown that there are several other forms of economic benefit from basic research, and that new useful knowledge is not necessarily the principal type of benefit. This review has proposed a classification scheme based on six categories of benefit.¹⁹

The first category relates to basic research as a source of new useful knowledge, while the second consists of new instrumentation and methodologies. As we have seen, the transfer of a new instrument from basic research to industry can open up new technological opportunities or dramatically alter the pace of technological advance. Thirdly, there are the skills developed by those involved in carrying out basic research, especially graduate students, which can also lead to substantial economic benefits as individuals move on from basic research, carrying with them both codified and tacit knowledge. The tacit knowledge and skills generated by basic research are especially important in newly emerging and fast-moving areas of science and technology. A fourth type of benefit stems from the fact that participation in basic research is essential if one is to obtain access to national and international networks of experts and information. Fifthly, basic research may be especially good at developing the ability to tackle and solve complex problems — an ability that often proves of great benefit in firms and other

organisations confronted with complex technological problems. Lastly, basic research may lead to the creation of ‘spin-off’ companies, where academics transfer their skills, tacit knowledge, problem-solving abilities and so on directly into a commercial environment. However, the available evidence is not so convincing as to the importance of this form of benefit compared with the others mentioned above.

The relative importance of the different forms of economic benefit distinguished here varies with scientific field, technology and industrial sector — i.e. there is great *heterogeneity* in the relationship between basic research and innovation. Consequently, *no simple model of the nature of the economic benefits from basic research is possible*. In particular, the traditional view of basic research as a source merely of useful codified information is too simple and misleading. It neglects the often benefits of trained researchers, improved instrumentation and methods, tacit knowledge, and membership of national and international networks. It should not, therefore, be used on its own as the basis for policy measures. In short, the overall conclusions emerging from the surveys and case studies are that: (i) the economic benefits from basic research are both real and substantial; (ii) they come in a variety of forms; and (iii) the key issue is not so much whether the benefits are there but how best to organise the national research and innovation system to make the most effective use of them.

This brings us back to the issue of the rationale for public funding of basic research. Governments are under increasing pressure to justify public expenditure on basic research and the traditional justification for public funding of basic research (as first set out by Nelson and Arrow) needs to be extended. Not only is basic research a source of codified information but it also yields a variety of other forms of economic benefit. A more effective rationale for the public support of basic research should take these fully into account. Such a rationale has yet to be constructed. However, this review of the literature has pointed to some of the likely constituent elements. These include the argument of Klevorick et al. (1995) and others that basic research creates technological opportunities, and the view of Callon (1994) that basic research provides a source of new interactions, networks and technological options, thus

¹⁹ As one referee has pointed out, the first category of benefit is concerned more with the production of knowledge, while the others focus on different mechanisms for the transfer and appropriation of knowledge. This brings us back to the thesis of Callon (1994) that scientific knowledge is not a public good because publication alone is not sufficient for the transfer and appropriation of that knowledge.

increasing technological diversity. Also relevant here is the work of Rosenberg, Pavitt and others showing the importance of basic research as a source of (i) the skills (particularly those based on tacit knowledge) required to translate knowledge into practice, (ii) an enhanced ability to solve complex technological problems, and (iii) the ‘entry ticket’ to the world’s stock of knowledge, providing the ability to participate effectively in networks and to absorb and exploit the resulting knowledge and skills.

This new rationale for public funding of basic research also needs to take into account the debate about the changing nature of research. Gibbons et al. (1994) have suggested that nature of knowledge production is shifting toward ‘Mode 2’, with greater collaboration and transdisciplinarity and with research being conducted ‘in the context of application’. They argue that, in this new mode²⁰ of knowledge production, the distinction between what is public and private in knowledge production and therefore in science has become blurred, if not irrelevant. David (1995) has disputed these claims, arguing that the institutions of public science such as peer review and publication provide the standards of trust and authority essential not only for the effective performance of research but also for the formulation of public policy and the provision of information for societal choices (David, 1995).²¹

In recent editions of *Research Policy*, there has been a heated debate between Kealey and David about the benefits of such public investment (Kealey, 1996, 1998; David, 1997). This review finds convincing evidence to support the idea that there are considerable economic benefits to the public funding of basic research. These benefits are often subtle, heterogeneous, difficult to track or measure, and mostly indirect. Publicly funded basic research should be viewed as a source of new ideas, opportunities, methods and, most importantly, trained problem-solvers. Hence, support for basic research should be

seen as an investment in a society’s *learning capabilities*.

6.2. Policy implications

What are the policy implications that follow from this review of the literature? As we have seen, although its economic benefits are hard to quantify, basic research is crucial for the strategic position of industrialised nations in the world economy, and for remaining at the leading edge of technology. This has been true in the past (especially in chemicals and pharmaceuticals) and will remain true in the future as new technologies draw increasingly on the outputs of basic research, on leading-edge scientific problem-solvers, and on the emerging fields based on a combination of scientific and technological know-how.

However, for various reasons emerging from this review, it is difficult to arrive at simple policy prescriptions. One reason relates to the variations in the forms of interaction between basic research and innovation, and in the relative importance of different forms of economic benefit with scientific field, technology and industrial sector.²² Secondly, there is the dependence of new products and processes on a range of technologies, and the dependence of new technologies on a large number of scientific fields; another way of expressing this is in terms of growing technological complexity and the need to ‘fuse’ previously separate streams of science or technology. A third reason concerns the importance of ‘spillovers’, including both geographical effects and the interactions between one form of activity and another. In short, there can be no simple unified policy for basic research.

Nevertheless, several policy lessons emerge from this review. First, policies must ensure that basic research is closely integrated with the training of graduate students, with the latter carried out in organisations at the forefront of their field. This has implications for the appropriate mix of public funding of basic research in universities and in central

²⁰ Some have questioned whether this is a ‘new’ mode or merely a return to a form of knowledge production more common in the 19th and earlier part of the 20th Centuries.

²¹ Others might dispute David’s notion of the scientific process (e.g. Fuller, 1997).

²² This has implications for national ‘Foresight’ exercises where the approach adopted in different fields and sectors needs to be sufficiently flexible to take account of these differences.

government research institutes.²³ Secondly, given the contribution to innovation which can flow from new instrumentation, research grants should include adequate resources for accessing the latest instrumentation, for developing experimental facilities and new methodologies, and for funding technicians to assist in these tasks. Thirdly, the evidence that skilled graduates who enter industry are a major channel through which basic research is transformed into economic benefit suggests that policies should be directed towards increasing the industrial recruitment of qualified scientists and engineers, particularly by firms that currently lack this resource. Fourthly, since a single piece of basic research may contribute to many different technological and product developments, and those developments may, conversely, draw upon a number of research fields, nations need a portfolio-based approach to the public funding of basic research — a portfolio both in terms of research fields and technologies but also in terms of a full range of mechanisms and institutions for ensuring that the potential benefits of publicly funded research are transferred and exploited successfully. Fifthly, the return from research depends crucially on having access to the outputs of publicly funded basic research, whether skilled people, techniques, instrumentation or other outputs. Without access to these, none of the downstream benefits are likely to be captured.

A sixth and final policy conclusion is that no nation can ‘free-ride’ on the world scientific system. In order to participate in the system, a nation or indeed a region or firm needs the capability to understand the knowledge produced by others and that understanding can only be developed through performing research. Investments in basic research enable national actors to keep up with and, occasionally, to contribute to the world science system.²⁴ Yet

the research reviewed in this paper does not suggest how much public support should be provided nor in what areas it should be invested. Currently, we do not have the robust and reliable methodological tools needed to state with any certainty what the benefits of additional public support for science might be, other than suggesting that some support is necessary to ensure that there is a ‘critical mass’ of research activities. The literature available has shown that there are considerable differences across areas of research and across countries and that additional research is needed to better define and understand these differences. This limitation in current science policy research should not be seen as implying a need for less government funding of science. Rather, it indicates that public funding for basic research is, like many areas of government spending (e.g. defence), not easy to justify solely in terms of measurable economic benefits.

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²³ We are grateful to the referee who made this point.

²⁴ Nelson and Wright (1994) have suggested that some form of modified free-riding might have been possible in the 1970s and 1980s as Japan and other Asian countries were able to exploit areas of Western research and to make more rapid advances in their technological capabilities. Whatever the merits of this claim, these countries have substantially increased their investments in basic research in the 1990s (OECD, 1999, p. 33), which suggests that free-riding, at least in its ‘pure’ form, is no longer feasible.

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