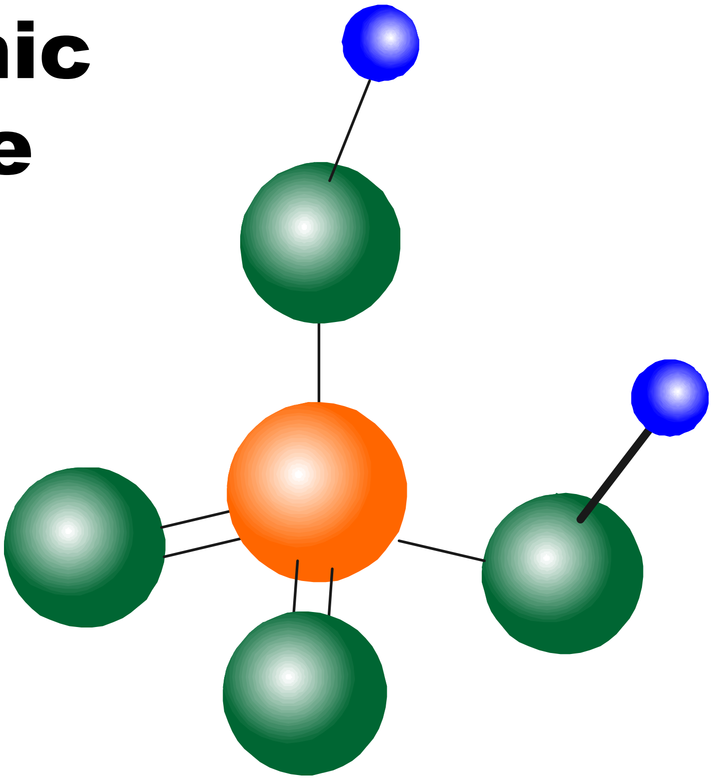
HM Treasury

The Relationship Between Publicly Funded Basic Research and Economic Performance



- A SPRU Review

REPORT PREPARED BY SCIENCE POLICY RESEARCH UNIT,
UNIVERSITY OF SUSSEX, FOR HM TREASURY

THE RELATIONSHIP BETWEEN PUBLICLY FUNDED BASIC RESEARCH AND ECONOMIC PERFORMANCE

A SPRU REVIEW

Ben Martin and Ammon Salter

with

Diana Hicks, Keith Pavitt, Jacky Senker,

Margaret Sharp and Nick von Tunzelmann

Science Policy Research Unit
University of Sussex
Falmer, Brighton
BN1 9RF, UK

July 1996

Report prepared for HM Treasury

PREFACE

This study was commissioned by HM Treasury. It was carried out by a team of researchers at the Science Policy Research Unit (SPRU), University of Sussex. The team was led by Ben Martin and consisted of Ammon Salter, Keith Pavitt, Diana Hicks, Jacky Senker and Nick von Tunzelmann. Other SPRU colleagues made substantial inputs, in particular Martin Bell, Michael Gibbons and Mike Hobday who provided extensive comments on a preliminary draft. The team also benefited from the help of the SPRU Library staff.

In addition, SPRU drew upon its network of international contacts to obtain further inputs and comments, with particular help coming from James Buwalda, Paul David, Richard Nelson, Stephen Popper, Rikard Stankiewicz, Edward Steinmueller and Peter Swann. Other useful feedback was provided by Craig Pickering and John Dowie (both at the Treasury), John Barber (DTI) and Derek Barker (OST).

The views in this report are those of the authors and are not necessarily those held by HM Treasury.

CONTENTS

EXECUTIVE SUMMARY 6

1.0 INTRODUCTION 10

2.0 DEFINITIONS AND APPROACH 11

2.1 Definitions and scope 11

2.2 Methodological approach and sources 12

3.0 CONCEPTUAL AND METHODOLOGICAL OVERVIEW 12

3.1 The nature of the economic benefits of basic research 12

3.2 Methodological approaches to measuring the economic benefits 13

4.0 ECONOMETRIC STUDIES 14

4.1 The relationship between research and productivity 14

4.2 Spillovers and regional or localised effects 19

4.3 Measuring rates of return to basic research: the contributions of Mansfield 22

5.0 DIFFERENT TYPES OF BENEFIT FROM BASIC RESEARCH 24

5.1 Increasing the stock of information 25

5.2 New instrumentation and methodologies 29

5.3 Skilled graduates 32

5.4 Professional networks 35

5.5 Technological problem solving 37

5.6 Creation of new firms 45

6.0 BASIC RESEARCH IN THE UNITED KINGDOM 46

6.1 How companies in the UK use basic research 46

6.2 Basic research and UK competitiveness 48

6.3 The chemical and pharmaceutical industries - a special case? 49

6.4 UK basic research and the location of corporate R&D 51

6.4.1 Foreign Multinationals' R&D Investment in the UK 52

6.4.2 European Multinationals' R&D Investments in the US 53

7.0 FOREIGN EXPERIENCES 54

7.1 Determining the level of expenditure on basic research 54

7.2 Expectations regarding basic research and ensuring value for money 57

8.0 CONCLUSIONS 59

8.1 Main findings 59

8.1.1 Econometric studies 59

8.1.2 Studies of different forms of economic benefit from basic research 60

8.1.3 Basic research in the United Kingdom 61

8.1.4 Foreign Experiences 62

8.1.5 The rationale for public funding of basic research 62

8.1.6 Policy implications 62

8.2 Conclusions on the six issues 63

APPENDICES 65

A1 Bibliography 65

A2 Recommendations for future research 74

EXECUTIVE SUMMARY

INTRODUCTION

1. The relationship between publicly funded basic research and economic performance is an important one, given the considerable sums of government money spent on basic research. This report reviews and assesses the academic literature on that relationship.

2. Among the issues addressed are the effect of publicly funded basic research on productivity, the impact on specific industries, the availability of research skills and their influence on the location of industrial R&D, UK companies' awareness of publicly funded basic research, whether explicit criteria are used overseas to determine the level of funding for basic research, and the benefits that foreign governments expect from publicly funded basic research. We also re-examine the rationale for public funding of basic research.

3. There are two main views on the nature of the economic benefits from basic research. According to the 'public good' argument, basic research yields economically useful information that can be used by firms to develop new products and processes. However, because of the inability of firms to capture all the benefits from basic research, firms tends to under-invest in basic research. To compensate for this, governments need to fund basic research. In the second view, scientific knowledge is seen as embedded in individuals and organisations, and the main benefits flow through training and networks. Public funding is needed to provide training and to maintain the nation's access to international networks.

4. There are three main approaches to measuring the economic benefits from basic research: (i) econometric studies (e.g. of rates of return); (ii) surveys (e.g. of the views of industrial R&D managers); and (iii) case studies (e.g. tracing the research inputs to innovations). The academic literature on each of these is examined here.

ECONOMETRIC STUDIES

5. There have been various econometric attempts to estimate the impact of research on productivity. Virtually all have found a positive rate of return, and in most cases the figure has been comparatively high. However, such studies have been beset with measurement and conceptual problems, in particular an over-emphasis on just one of the forms of benefit from basic research - its ability to generate useful new information.

6. There is a substantial econometric literature on spillovers and related phenomena which suggests that countries need their own strong basic research. In addition, personal links and mobility are vital to link basic research to technological development, which points to the need to integrate basic research with postgraduate training.

7. Work by Mansfield in particular shows that one can arrive at an estimate of the rate of return on basic research. Again, the result is impressively large (e.g. 28 per cent). However, the approach involves a number of assumptions that are open to question, for example about (i) the relationship between spending on basic research and the much larger investments in development, production, marketing and diffusion; and (ii) the complex indirect contributions from basic research to technology - contributions which vary greatly across fields and sectors. Another important limitation is that such studies measure average rather than marginal rates of return.

SURVEYS AND CASE STUDIES OF DIFFERENT TYPES OF BENEFIT FROM BASIC RESEARCH

8. Our review of the literature suggests that there are six main forms of economic benefit from basic research:

(i) basic research as a source of *new useful information*;

(ii) the creation by basic researchers of *new instrumentation and methodologies*;

(iii) *skills* developed by those engaged in basic research (especially graduate students) which yield economic benefits when individuals move from basic research carrying codified and tacit knowledge;

(iv) participation in basic research to gain *access to networks of experts and information*;

(v) the fact that those trained in basic research may be particularly good at *solving complex technological problems*, an ability that often proves of great benefit in industry; and

(vi) the creation of *'spin-off' companies*.

9. The numerous case studies and surveys illustrating these various forms of economic benefit suggest that only a comparatively small proportion of the benefits flow in the form of new useful knowledge that is directly incorporated in new products or processes.

10.The relative importance of these different forms of benefit varies with scientific field, technology and industry. In other words, there is great *heterogeneity* in the relationship between basic research and innovation. As a consequence, no simple model of the nature of the economic benefits from basic research is possible. This poses a challenge in trying to arrive at the optimum structure for government support of basic research.

BASIC RESEARCH IN THE UNITED KINGDOM

11.The literature on the relationship between companies and publicly funded basic research shows that the use companies make of such research varies widely across sectors. Basic research contributes both through trained scientists and as source of new useful knowledge. Much of the contribution from publicly funded basic research to industry comes in the form of small and often largely invisible flows. Companies need a strong internal research capability in order to use and exploit external knowledge effectively.

12.There is some literature on basic research and national competitiveness. At the macro-level, the relationship between basic research and UK industrial performance is unclear. At the sector level, in the case of chemicals and pharmaceuticals, there is both a strong science base and internationally competitive industrial performance, with many of the links between basic research and industry being relatively direct. In electronics, in contrast, industrial performance has been weaker and the science base is also less strong. However, of greater importance here may be the more indirect, longer-term and multi-step nature of the links between basic research and commercial exploitation.

13.Data on the location of corporate R&D shows that UK industrial R&D is comparatively internationalised. Approximately 45% of UK company R&D is performed overseas, and about 20% of company R&D in UK is carried out by foreign companies.

This high level of internationalisation brings substantial spin-off benefits for the UK in terms of being integrated more fully into international research networks.

14.Investment by UK companies overseas, in particular in US biotechnology, is driven by the need to access US knowledge and capabilities together with other factors such as the large North American market, access to raw materials and the US regulatory regime. In some cases, dissatisfaction with the UK science base may also be a factor. Such overseas links may help to strengthen a company's research capabilities, but they may also exacerbate existing weaknesses in UK basic research.

15.The high level of investment by overseas companies in R&D in the UK is driven by the desire to access skills, the existence of strong university research teams, and the relatively low costs of British researchers.

FOREIGN EXPERIENCES

16.There is no evidence that other countries use systematic criteria to determine the level of funding for basic research. Certainly, there has been no attempt to link it to the magnitude of the economic benefits that basic research generates. However, in most industrialised countries, there is an emphasis on strengthening basic research to enhance technological innovation, industrial competitiveness, and economic and social development.

17.The expectations that the state and society have in relation to basic research are changing. We are witnessing the emergence of a new 'social contract' for basic research under which the public and government expect more direct and specific benefits from their investments in this research. Technology foresight offers one means to link research to longer-term economic and social benefits. However, there are currently no methods for estimating the value for money from publicly funded basic research in a reliable manner.

THE RATIONALE FOR PUBLIC FUNDING OF BASIC RESEARCH

18.The traditional justification for public funding of basic research needs to be expanded. In addition to the 'public good' view of science as a source of useful information, we also need to take into account the other forms of economic benefit from basic research .

19.Such a rationale has yet to be constructed but its components are likely to include the view of basic research (i) as a source of new interactions, networks and technological options, (ii) as a means to generate new skills especially tacit skills and problem-solving abilities, and (iii) as an entry ticket to international networks of experts and information.

CONCLUSIONS ON THE SIX ISSUES

20.Publicly funded basic research seems to have had a substantial impact on productivity and that trend is likely to continue. However, the methodologies to quantify this effect are seriously flawed. In particular, they tend to ignore the non-information forms of output or benefit.

21.The relationship between basic research and performance in specific industries depends as much on the attitude and approach of companies as on the strength of the basic research. In the UK, that attitude seems to be more positive and far-sighted in companies drawing upon the results of basic research in chemistry and biology than those drawing upon physics and much of engineering research. However, just as important may be the fact that the latter companies are faced with the multi-link chains between basic research and commercial exploitation that are more difficult to nurture and manage.

22.Until recently, most multinational companies conducted the great majority of their research in their home country. However, evidence is emerging that some are now locating research activities in areas which are particularly rich in scientific skills.

23.There is only a small amount of evidence on how aware British companies are of publicly funded basic research, or on whether they are better or worse informed than foreign competitors. Although many are aware of government-funded collaborative research programmes, with a few prominent exceptions they do not appear to adopt as systematic approach to gathering intelligence about scientific research from around the world as some of their competitors in Japan and the United States.

24.There is no sign that explicit criteria are used in other countries to determine the level of public funding of basic research. That level depends partly on general perceptions as to how important a role basic research is likely to play in relation to the development and exploitation of new technologies, but just as important are other factors such as the prevailing government philosophy and international comparisons or pressures.

25.Government expectations about the benefits from basic research are changing. A new ‘social contract’ is emerging in which there are more specific expectations that basic research should generate economic and social benefits in return for the substantial public funds that it receives.

THE RELATIONSHIP BETWEEN BASIC RESEARCH AND ECONOMIC PERFORMANCE

1 INTRODUCTION

The relationship between publicly funded basic research and economic performance is an important one. Considerable sums of government money are spent on basic research in universities, Research Council institutes and elsewhere, yet scientists and Research Councils constantly argue that more is needed. At the same time, the UK Government, like that in most advanced industrial nations, is faced with many competing demands for public funding. To many, the benefits associated with public spending on, say, health or education are more obvious than those stemming from expenditure on basic research. However, as this report will show, there is extensive evidence from previous academic work that basic research does lead to substantial 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 latest academic research. To this end, the report summarises and assesses academic literature on the relationship between publicly funded basic research and economic performance.

We were asked to address the following issues:

- the extent to which publicly funded basic research, by adding to the stock of knowledge and competencies, increased the level or rate of growth of national productivity; this includes a critical assessment of the methodologies used for assessing the benefits of basic research as well as of the conclusions reached;
- the extent to which the UK's comparative strength in specific industries is attributable to past public investment in basic research in scientific or technological areas associated with those industries;
- the extent to which research-intensive businesses concentrate, or might in future concentrate, their research, development and production in countries (or areas) with a comparatively greater supply of high quality research skills;
- the extent to which UK businesses are aware of publicly funded basic research and its outcomes in areas of science relevant to their businesses and, where they are, whether the information available to them about publicly funded science in the UK is better than information about equivalent science being funded abroad;
- the criteria used by governments in other leading industrial countries (e.g. the United States, Japan, Germany, France, Netherlands and Australia) in determining the level of funding for basic research and their levels of expenditure;
- what benefits those governments expect to see from basic research and how they assess the value for money for this investment.

As part of this, we have also examined the traditional rationale for public funding of basic research and, as we shall see, have found it wanting in the light of recent research. Although a complete and satisfactory new rationale for government funding of basic research has yet to be constructed, we point to some of the likely constituent elements of that new rationale. Lastly, one further purpose of the project was to act as a scoping study for possible future research on the topic. We have therefore attempted in Appendix 2 to identify key issues that need further research and suggest how they might best be approached.

In Section 2, we begin by defining the area of research covered in this study and outline the approach adopted and the sources upon which we drew. Section 3 examines the nature of the economic benefits of basic research and the different methodological approaches to measuring them. Sections 4 to 7 then critically review and synthesise the main types of academic literature of relevance here. Of these, the first deals with econometric studies on the relationship between research and productivity, 'spillovers', and the rates of return to research. Section 5, which is the most substantial of the sections, distinguishes the main types of economic benefit from basic research and discusses findings from previous studies on each of these. This is followed in Section 6 by a section on basic research in the United Kingdom which covers the issues of how companies in the United Kingdom use basic research, the UK's comparative advantages, and the location of corporate R&D. Lastly, foreign experiences in relation to determining expenditures on basic research, deciding the distribution of such funds and assessing the economic benefits are briefly summarised in Section 7. The final section identifies the lessons from the literature reviewed and the conclusions to be drawn.

2 DEFINITIONS AND APPROACH

2.1 Definitions and scope

The report is concerned with primarily **basic** research. 'Basic research' is taken to include both 'curiosity-oriented' research (experimental or theoretical research undertaken primarily to acquire new scientific or technical 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] However, much of the literature reviewed here uses other terms such as 'science', 'academic research' or just 'research', categories that are not identical with 'basic research' although they overlap considerably. We have chosen to use the terminology adopted by the authors themselves since to rephrase everything in terms of 'basic research' would risk distorting their arguments or conclusions.

The study focuses on the **economic** benefits from basic research rather than the social, environmental or cultural benefits. Nevertheless, it should be recognised that there is a rather 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? In view of this uncertainty, we define 'economic' quite broadly. It should also be stressed that the study considers not only economic benefits in the form of directly useful knowledge but also other, perhaps less obvious economic benefits such as competencies, techniques, instruments, networks and the ability to solve complex problems. As we shall see, it is often extremely difficult or even impossible to quantify these benefits with precision. This does not mean, however, that such benefits are not real nor that they are not substantial.

Lastly, the study concentrates on **publicly funded** basic research. This includes much of the basic research conducted in universities, Research Council institutes and hospitals. However, again the boundary is somewhat indistinct since some public funds

---

[1] This definition of basic research 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 can, in turn, have an impact on basic research.

go to support research that is conducted on the basis of collaboration between universities and industry.

2.2 Methodological approach and sources

The SPRU team began by identifying relevant literature and other material. This was then collected, analysed and synthesised to draw out the main conclusions. For more specialised areas, individual members of the SPRU team with the appropriate expertise identified key issues and conclusions emerging from previous academic research, and produced a critical overview and synthesis. In addition, the team took advantage of SPRU's extensive network of international contacts, a number of whom were asked to provide inputs or advice.

As regards sources, this study is based largely on published literature. This includes not only original research contributions but also a small number of previous reviews of the subject (e.g. Office of Technology Assessment, 1986; Smith, 1991; Congressional Budget Office, 1993; Steinmueller, 1994; Popper, 1995). In addition, members of the SPRU team drew upon their own empirical (and theoretical) work (for example, material from interviews and case studies).

3 CONCEPTUAL AND METHODOLOGICAL OVERVIEW

3.1 The nature of the economic benefits of basic research

There are two main approaches to understanding the nature of the economic benefits from publicly funded basic research. The first approach focuses on the concept of public goods. According to the conventional 'public good' argument in its simplest form, public funding for basic research creates new sources of economically useful information, information that can then be used by private firms to develop new products and processes. This information is often non-rival, non-excludable and durable.[2] In a market society, because of the inability of firms to capture all the benefits of their research, there is a tendency to under-invest in basic research. Government funding counteracts this tendency by bearing some of the social costs of the development of new scientific information (Nelson, 1959; Arrow, 1962). In short, this first approach to understanding the economic benefits of science stresses the importance of publicly funded basic research as a source of new *information* for use by firms and others.

The second approach, in contrast, emphasises the social or individual 'embeddedness' of scientific knowledge. It suggests that scientific knowledge is often person-embodied or the outcome of a set of social interactions. In this context, scientific knowledge resides in individuals, independently or as a collectivity. Adherents of this second approach tend to view the benefits of publicly funded science as flowing mainly from *training and the development of networks* - that is, from the interactions of individuals. Many who take this perspective would argue that the spillover effects emphasised by the first approach will be very restricted unless such training and interaction takes place. As we shall see later, it is this second approach, with its emphasis on learning, tacit knowledge, skills, methodologies, problem-solving ability and networks, that is more in tune with the results emerging from much recent work on the nature of basic research and the economic benefits it generates.

At first sight, it might seem reasonable to attempt to amalgamate these two perspectives. In an important reassessment of private research and development (R&D), Cohen and Levinthal (1989) argued that it has 'two faces'. One face is the obvious one of generating new knowledge from within; the other (and in their view a much more important one in

---

[2] These terms are defined in Section 5.1 below.

most firms) is that of allowing the ‘absorption’ of new knowledge generated outside the firm. With certain modifications, this model might have some application to the case of publicly funded basic research. Indeed, some fusing of the two approaches outlined here may be necessary if we are eventually to arrive at a new and more satisfactory rationale for public funding of basic research.

3.2 Methodological approaches to measuring the economic benefits of basic research

There are three general methods for measuring the benefits of basic research: (i) *econometric studies*; (ii) *surveys*; and (iii) *case studies*. Let us consider each of these in turn.

The econometric approach is well suited to obtaining a picture of the broad effect of scientific research on a nation or a region. It generally relies on large databases analysed using statistical techniques and has the benefit of providing aggregate data. Econometric studies offer a mechanism for measuring the social rates of returns to research, either through a macro-level approach or through micro-level case studies. However, there are numerous empirical difficulties in measuring scientific knowledge and its contribution to technical change and economic welfare. In particular, there is the problem of ‘tracing’ the extent of information derived from basic research that is brought into use in any particular innovation. Since such transfers are not priced or sold and are rarely adequately recorded by other means, the extent of their application remains unknown. In addition, one must remember that basic research is not directed primarily towards applied purposes, and spending on it is very much smaller than that on applied research, development, production and commercialisation. It is therefore very difficult to establish what contribution basic research makes to the development of a technology merely by measuring the total funds spent at the basic research stage and then looking at the subsequent outcomes. (There are also serious theoretical and measurement problems associated with the presumption that R&D ‘causes’ innovation.)

In these circumstances, the lack of correlation between national levels of spending on basic research and of economic performance (e.g. rates of productivity growth and exports) is hardly surprising, while there is a significant correlation between such performance and business-funded R&D activities (Fagerberg, 1994). Perhaps more interestingly, there is a correlation between national levels of basic research and of business-funded R&D. The UK, however, is an outlier, British firms apparently being more reluctant than many of their overseas competitors to recognise the importance of research to their competitiveness (Patel and Pavitt, 1987). Whether this will persist in future is an important subject for analysis and debate.

Surveys provide a rather more robust approach. They have been used to estimate how much basic research contributes to products and processes. They also examine the links between technology and science, providing a detailed picture of the role of basic research in the process of innovation. Such surveys have been conducted in the United States (the Yale survey, and the work by Mansfield) and in Europe (the PACE study). The results reveal that the importance of science - both basic and applied - varies across industrial sectors, and that the links between science and technology are subtle, indirect and varied. Such surveys are extremely useful in understanding the broad patterns of relations among different actors in a system of innovation, but they have various limitations. In particular, the surveys carried out have focused almost entirely on a limited number of large firms. Furthermore, they obtain information from industrial R&D managers who tend to stress the importance of sources of technical knowledge within their firms and who are unlikely to be fully aware of the historical links between their research activities and basic research conducted elsewhere.

The third approach involves case studies of particular sectors or technologies, the most influential of which probably remain the pioneering TRACES studies funded by the US National Science Foundation in the 1960s and 1970s. A case study attempts to trace all the historical antecedents to an innovation including indirect links to science such as those based on skills, equipment and networks. Case studies also show how these links evolve. However, case studies face numerous problems. They inevitably provide an incomplete picture of the varied nature and extent of the links between basic research and application. They are also difficult to generalise beyond the situation studied, one which was chosen by the researcher for particular reasons. Nonetheless, only case studies provide a mechanism for tracing in detail the links and processes from basic research to application, and they are therefore valuable in ascertaining the economic benefits of publicly funded basic research.

4 ECONOMETRIC STUDIES

4.1 The relationship between research[3] and productivity

Following the work of Solow and Denison, several economists have attempted to measure the portion of economic growth accounted for by technical progress. Early models of growth focused on labour and capital inputs into production. These studies did not attempt to measure the contribution of technical progress directly, but "treated it as a residual factor accounting for growth" (Mairesse and Sassenou, 1991, p. 10). In effect, technology was equated with productivity (of labour and capital) and so had no independent role to play in explaining productivity growth. As a result, the impact of technical change on growth is not accounted for in any direct way. These early studies consequently had little to say about the role of research in growth.

In practice, measuring the impact of technical progress has turned out to be a difficult task for economists. There are difficulties in measuring both economic and technological performance, together with the usual econometric problem of having to draw inferences from non-experimental data - i.e. from the real world in which there are many competing interactions (Griliches, 1995, p. 52). To these has to be added the theoretical problem of identifying an adequate model for explaining the links which occur.

There are a small number of studies which have tried to assess the payoff to publicly funded R&D, usually in comparison with privately funded R&D (e.g. Griliches, 1986; Griliches, 1995, p. 62). The evidence to date seems to indicate a relatively small return to public as opposed to private R&D. However there are serious limitations to these assessments. Typically the studies are conducted on annual data and examine short-term effects, whereas the payback to basic research, in particular, is likely to be spread over the very long term. Indeed, attempting to capture adequately the returns to publicly funded research is much more difficult than estimating the returns to industry-funded R&D, much of which involves technical services and incremental product development. Secondly, the identification of the economic benefit from much basic research depends on the involvement of, and information from, industrial R&D organisations and staff. Such bodies may be under rather more pressure to show that their own R&D is contributing to the well-being of the firm than to show that publicly funded research is contributing in this way. This may therefore lead to an inherent bias in favour of under-estimating the contribution of publicly funded research. Thirdly, the R&D data utilised, usually federal expenditures by the US government, include a very large component for military R&D. It is widely accepted that the economic return to military R&D is likely to be low (or even negative), partly because the returns being aimed at are more likely to be political or some

---

[3] Much of the literature reviewed in this section tends to deal with 'research' or 'R&D' rather than just 'basic research'. However, since basic research is an important component of these broader categories, it is worth briefly examining the main findings here.

TABLE 1 ESTIMATES OF RETURN ON AGRICULTURAL R&D AND R&D SPILLOVERS

Authors	Subject	% Rate of Return to Public R&D	Time Period
Griliches (1958)	Hybrid Corn	34-40	1949-59
	Hybrid Sorghum	20	1949-59
Peterson (1967)	Poultry	21-25	1915-60
Schmitz-Seckler (1970)	Tomato harvester	37-46	
Griliches (1968)	Aggregate	35-40	
Evenson (1968)	Aggregate	28-47	1949-59
Davis (1979)	Aggregate	37	1964-74
Evenson (1979)	Aggregate	45	1948-71
Davis & Peterson (1981)	Aggregate	37	1974
Huffman-Evenson (1993)	Crops	45-62	
	Livestock	11-83	
	Aggregate	43-67	

Source: Griliches (1995) and OTA (1986)

other form rather than economic (the strategic benefit from military expenditure is not allowed for in the measurement of output, either).

Most econometric approaches towards the measurement of the economic benefits of research instead focus on the contribution to growth stemming from investments by private industrial firms themselves in research (both basic and applied) *and* development activities.

Hence, much of the econometric literature in this field is outside the purview of this review. This work shows consistent findings of “a significant positive and relatively high rate of return to R&D investments at both the private and the social level” (Griliches, 1995, p. 82). The results of these studies are summarised in Tables 1 and 2. Immediately apparent is the variation in the estimated rates of return by sector and by study. This suggests that econometric approaches to the measurement of the rates of return to investment in research are, at best, an imperfect science. For example, in his review of the econometric data relating to R&D and productivity, Griliches estimates that the “rate of return to [industrial] R&D lies mainly between 0.2 and 0.5 [i.e. 20-50 per cent], with most estimates falling in the lower part of this range” (*ibid.*, p. 56).

Such rates of return are nevertheless very impressive. Indeed, they are considerably larger than the rates of return generally expected from capital spending, which raises the question of why private businesses do not undertake more R&D. Answers to this question would take us far afield, but the inherent riskiness of research is evidently one consideration. Some of the individual activities assessed in the studies reported in Tables 1 and 2 were unusually successful (e.g. hybrid corn) and it may be that not

TABLE 2 ESTIMATES OF RATES OF RETURN TO INDUSTRIAL RESEARCH

Authors	Sample	Details of specification	% Rate of return to R&D	R^2
Minasian (1962)	United States 18 firms	Total productivity	25	.67
	Chemicals 1947-57	Value added		
Mansfield (1980)	United States 16 firms	Total productivity	27	.49
	Chemical and petroleum	Value added		
	1960-76			
Link (1981)	United States 174 firms	Total productivity	-.00	-.00
	33 firms Chemicals	Value added	.07	.14
	34 firms Machinery		.05	.02
	19 firms Transport eqpt		.15	.03
Link (1983)	United States 302 firms	Total productivity	6	.34
	1975-79	Sales		
Griliches and	United States and France	Sales	28	n/a
Mairesse (1983)	343 + 185 firms 1973-78	Sales	12	n/a
		Ind'y dummies		
Odagiri (1983)	Japan 370 firms 1969-81	Total productivity		
	Scientific Sectors	Sales	26	.04
	Other Sectors		-47	.01
Clark and	924 Business units	Sales	18	.59
Griliches (1984)	1971-80	Ind'y dummies		
		Total productivity	20	.15
		Sales		
		Ind'y dummies		
Odagiri and	Japan 135 firms 1974-82	Total productivity	17	.05
Iwata (1986)		Sales		
		Total productivity	11	.58
		Value added		
		Ind'y dummies		
Sassenou (1988)	Japan 394 firms 1973-81	Sales	69	.04
		Value Added	22	.02
		Value Added	-2	.65
		Ind'y dummies		
		Value Added	4	.66
		Ind'y dummies		
		Free Returns		
Goto and	Japan 1975-84	Total productivity	42	.80
Suzuki (1989)	13 firms Drugs	Value added		
		Total productivity	23	.76
		R&D capital		
	5 firms electrical	Total productivity	22	.58
		Value added		
		Total productivity	53	.62
		R&D capital		

TABLE 2 (CONT'D)

Authors	Sample	Details of specification	% Rate of return to R&D	R^2
Lichtenberg & Siegel (1989)	United States 5240 firms 1972-85	Total productivity Sales Ind'y dummies	13	.03
Fecher (1989)	Belgium 292 firms 1981-83	Total productivity Sales Ind'y dummies	13	.03
Griliches & Mairesse (1983)	United States 525 firms 1973-80	Sales	41	.07
		Sales Ind'y dummies	27	.25
		Sales Ind'y dummies Free returns	25	.27
	Japan 406 firms 1973-80	Sales	56	.09
		Sales Ind'y dummies	30	.50
		Sales Ind'y dummies Free returns	20	.53

Source: Griliches (1995) and OTA (1986)

enough 'failures' have been accounted for in these calculations. However, the results seem to hold up, although not quite so strongly, at an aggregate level. In a study of 1000 of the largest US firms during the 1970s, Griliches found that those spending a larger fraction of their R&D on basic research were more productive and had a higher level of output relative to their other measured inputs (including R&D capital). Moreover, this effect was relatively constant over time (*ibid.*, p. 62).

Econometric attempts to measure the economic benefits of basic research have usually been based on a production function model. Such models take a measure of 'R&D capital' and add this to measures of other factors of production, such as labour and capital, which are regarded as the inputs. Early production function models tended to be based on rather small samples of firms, but more recent studies have used more aggregate figures. Another limitation is that production function approaches assume, to varying degrees, invariant production techniques among firms; in other words, given a set of market responses, firms will substitute labour and capital identically. This is clearly a gross over-simplification of reality; although perhaps helpful for empirical purposes, it is difficult to maintain in the face of research on firm behaviour (which shows that such behaviour is heavily dependent on the firm's history and context).

Production function representations of firms' production processes are therefore simply 'mental models' of the way in which the world works: "It has not been proven that such production functions exist or take the form assumed by economists" (OTA, 1986, p. 14). In many studies based on the production-function approach, it is assumed that the inputs are entirely separable, and no attempt is made to take into account the interactions between each of them; often the labour, capital and technological inputs into production are complementary or closely related, as are also the inputs into basic research and into applied research and development (Nelson, 1982). Frequently, it is supposed that the specified inputs are homogeneous, with no differentiation being made between, say, skilled and unskilled labour.

Moreover, measuring 'R&D capital' (or the stock of technological knowledge generated by previous R&D, broadly defined) is a difficult task empirically, whether at the level of the firm, the sector or the nation as a whole. It is also difficult to find a method to deflate (or allow for the speed of depreciation of) the value of R&D capital over time, given the non-rival and non-excludable aspects of R&D (discussed in Section 5.1). Even more problematically, such approaches are limited by virtue of the fact that R&D is merely one factor in the process of technical change. For example, Denison (1985) has suggested that R&D accounts for only 20 per cent of all technical progress. Therefore, econometric approaches which focus solely on R&D, and especially industrial R&D, fail to capture many of the activities contributing to technical progress and should be used with considerable caution.

Another fundamental problem is that the 'output' - in terms of greater productivity, profits and so on - is assumed to come from the higher level of R&D inputs provided by the country or sector in question. In practice, partly because of the spillover consequences associated with the 'publicness' of basic research, it is usually impracticable to match outputs directly to the specified inputs. The returns reaped in, say, crops (to take one sector referred to in Table 1) are likely to involve the spin-off benefits from other sectors, such as agricultural machinery or biotechnology; one should therefore also take into account R&D conducted in those upstream sectors which feed through to crops. In this respect, the returns to R&D on crops will be overstated. Conversely, the R&D undertaken in crops may benefit other sectors that use crops as inputs or other areas of R&D; to this extent, the returns to R&D on crops are understated. The same argument can be extended to the aggregate level, where the spillovers spread across countries rather than across sectors.

Two procedures have attempted to overcome this problem. In recent American studies, it has become common to insert an additional variable reflecting the overall national or global level of science and technology, as indicating the whole pool from which the spillovers may derive. This usually gives rise to significant values being returned for the national/global variable (at least in those results actually reported), but can be criticised for 'jumping out of the frying pan into the fire' - in this model, the assumption that there is no spillover is replaced by the assumption that all science or technology is a potential spillover. More specific assessments of spillovers are examined in the Section 4.2 below. The second approach is more defensible, but much more difficult to measure. This procedure uses input-output notions to relate R&D in each sector to returns in other sectors and vice versa. The primary research required to build such an input-output model is very great, and most studies have drawn upon the work of Scherer (1982) for the USA. Sterlacchini (1989) has applied the Scherer structure to a sectoral input-output table for the UK. Whether the US structure is applicable to other countries must remain in doubt; one possibility would be to use the SPRU innovations database as a suitable input-output indicator.

The problems in trying to gauge the effects of basic research are even greater. In the first place, the linkages from basic research to use in production are multiple and complex. Chemistry is used not just in the chemicals sector but also in a large range of user industries, and other academic disciplines like physics and mathematics have still more pervasive impacts. This is discussed more fully below in relation to 'multi-technology' companies (see Section 5.5). Secondly, the R&D inputs assessed for the private sector may understate the costs of technology deployed. For example, as we shall see later, one of the primary benefits of basic research for industry comes through the transfer of skilled graduates from academia to industry. In production function models, this role of basic research in increasing the ‘knowledge stock’ is ignored, particularly to the extent that its costs are met out of the public purse.

Furthermore, production function models do not consider the *process* of technical change. In reality, technical change can be a product of the production process, appearing through the incorporation of labour and capital inputs into the production process - including the employment of researchers as just described. This has been suggested by much recent research, not only in innovation studies but also in the so-called ‘new growth theory’. The ‘factors of production’, in this view, are not simply endowments but are capable of enhancement (Porter, 1990); they then become endogenous to the model. When the causal links run in the opposite direction, in this case from production to productivity, then the econometric procedures that use single-equation models will give biased and inconsistent estimates.

To summarise, virtually all econometric estimates of the impact of research on productivity have suggested positive and indeed impressively large rates of return. However, such attempts have been plagued by errors of measurement and errors of conception. The latter come mainly from weaknesses in theory as to how the R&D on one side and the economic or social aspects on the other are related. Investments in basic research are more often an investment in a learning capability, a capability to solve *complex* problems, than in the direct creation of new technologies, products or processes.

4.2 Spillovers and regional or localised effects

Among the more recent and arguably one of the most important new developments in thinking about the benefits of basic research is the econometric work which has focused on the notion of ‘spillovers’ from research and attempted to measure these. Often, these spillovers have a proximity element or a set of benefits spreading from one activity to the next - that is, “the productivity achieved by one firm or industry depends not only upon on its own research efforts but also on the level of the pool of general knowledge accessible to it” (Griliches, 1995, p. 64). There are two main forms of spillover identified in the economic literature: (i) those relating to geographical proximity; and
(ii) spillovers across sectors or activities. The latter has been briefly discussed in the previous section so we will concentrate on the former here. These geographical spillovers imply benefits for firms located near to research laboratories. The economic evidence is that there is a significant localisation effect in research activities and in the spillovers associated with them.

To begin with, collaboration within basic research tends to be localised. Recent work by Katz using bibliometric indicators[4] has shown that the occurrence of research collaboration between universities within a country is strongly influenced by geographical proximity. Looking at two-way collaborations within the United Kingdom, Australia and Canada, Katz found that “university-university collaboration decreases exponentially with distance and therefore occurs more frequently with partners who are geographically closer than with those further away” (Katz, 1994, p. 39).[5] This work points to the need for informal, face-to-face communication in the process of research collaboration and to the fact that additional distance raises the travel and time costs (Katz, 1994, pp. 40-41).[6]

---

[4] ‘Bibliometric’ indicators are based on scientific publications - for example, numbers of papers in international refereed journals, and number of times those papers are cited in subsequent scientific literature.

[5] ‘Social distance’ may also be a factor, although that is less relevant to the discussion here.

[6] Recent work by one of the co-authors (von Tunzelmann) on electronics multinationals also suggests that distance is a significant variable.

Jaffe has attempted to measure geographical research spillovers in the United States in order to determine the “real effects of academic research” (Jaffe, 1989). He examined trends in the production of patents assigned to corporations located in different US states over time and related these to industrial R&D and university research. He used patents as a proxy for innovative output. Adopting a production function approach, Jaffe measured the geographic coincidence of university and industrial research activity within individual states. He collected data on industrial and university R&D expenditures for 1972-1977, 1979 and 1981, for some 29 states (these represent approximately 80-85 per cent of US research and patenting). Academic research and patent technological classes were broken down into five categories: (i) drugs and medical technology; (ii) chemical technology; (iii) electronics, optics, and nuclear technology;
(iv) mechanical arts; and (v) other.

Jaffe’s analysis shows that spillovers from university research to commercial exploitation, as measured through patents, certainly exist. The effect is strongest for the pharmaceuticals, chemicals and electronics sectors. In addition, Jaffe found that there is an association between industrial R&D and university research at the state level in the US; establishing the direction of causality here is, as he admits, rather difficult but it appears that university research encourages industrial R&D but not vice versa. “Thus, a state that improves its university research system will increase local innovation both by attracting industrial R&D and augmenting its productivity” (*ibid.*, p. 968). The elasticity of corporate patents with respect to university research is also surprisingly high, indicating a substantial rate of corporate response (as reflected in patenting) and thus of social returns to university research.

Jaffe’s approach has a number of limitations:

(a) it is not clear whether US states are the appropriate unit for seeking geographical coincidence effects;[7]

(b) no explanation is offered of the mechanism for transferring academic results to corporate patents;

(c) the use of patents as an indicator has its flaws because not all innovations are patented and because patents differ widely in their economic impact;

(d) the production function approach to measuring the importance of research to industry faces several limitations (as we noted above).

In a similar study, Acs *et al.* suggest that, instead of measuring innovative output using patents, it is more fruitful to count numbers of innovations, for example, as listed in leading technology, engineering and trade journals in each manufacturing industry. The authors used figures for 1982 compiled by the US Small Business Administration. Such an approach is inherently subjective with only those innovations that receive written publicity being counted. Acs *et al.* use the same production function equation as Jaffe but substitute innovation counts for patents. Their findings are broadly similar to those of Jaffe but with two important differences. First, the impact of university spillovers is greater on innovation counts than on patented inventions. Secondly, the “impact of the geographical coincidence effect also is much greater on innovation activity than on patents, suggesting that spillovers from geographical proximity may be more important than Jaffe (1989) concluded” (Acs *et al.*, 1991, p. 366).

Feldman and Florida (1994) have also developed a spatial model to measure the geographic distribution of innovation sources in the United States. Using the same

---

[7] California, for example, has a larger economy and population than many nations.

database as Acs *et al.* (on US innovations reported in 1982), they analyse the technological infrastructure of a local area - that is,

> networks of firms that provide expertise and technical knowledge; concentrations of R&D that enhance opportunities for innovation by providing knowledge of new scientific discoveries and applications; and business services with expertise in product positioning and the intricacies of new product commercialisation. (*ibid.*)

They argue that the local technological infrastructure determines the capacity for innovation in different regions and shapes local patterns of innovation. Their research shows that different regions in the United States have developed specialised capacities for innovation in particular technologies and industrial activities. Using a model based on four variables (distribution of university R&D, industrial R&D expenditures, distribution of manufacturing, and distribution of producer services), Feldman and Florida suggest that university R&D is closely associated with industry R&D and also statistically correlated with the other variables. The authors argue that these four variables together represent the technological infrastructure of a region and determine that region's capacity for innovation. This research reinforces the view that geography is an important influence on the process of innovation. Locational advantages reflect cumulative investments in human and technological capabilities in specific places. "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 an underlying technological infrastructure" (Feldman and Florida, 1994, p. 226).

These locational linkages show up equally, if not more, strongly across countries. For example, Hicks *et al.* (1996) have analysed the articles published in learned journals by researchers in major science-based companies in Western Europe and Japan. A large proportion of these (one third in the case of Japanese company papers and one half in the case of European ones) involve collaboration between the company and another research organisation. Those collaborating partners are far more likely to be domestic than foreign. For example, the Japanese share of the world total of scientific publications is somewhere between 8 and 13 per cent (depending on the database used). If all potential collaborators around the world represented equally attractive partners, one would expect 8-13 per cent of the Japanese collaborative company papers to involve a Japanese partner. In reality, the numbers are almost exactly the opposite: 88 per cent of those joint papers involve a Japanese collaborator and only 18 per cent a foreign partner. In short, not all potential partners are equally attractive; those who are geographically closer and more similar in terms of language, history and culture are evidently more attractive to each other (*ibid.*). Similarly, Narin and Olivastro (1994) find a systematic bias across all major countries in the degree to which business firms cite, in their patents, scientific papers from their own country much more frequently than would be expected from the country's relative importance in world science.

Why does localisation occur? The R&D process is characterised by a great deal of interaction between individuals in firms and research institutions such as universities. In order to develop new forms of knowledge or to transfer existing forms of knowledge, research performers and users often need close, personal interaction, given the importance of know-how (i.e. tacit knowledge that cannot be codified). This need to 'be there' forces firms and individuals to congregate in particular localities in order to share and transfer information quickly and effectively. These lines of personal interaction, often informal in character, are important elements of the geographical constraint on innovation.

To sum up: the main policy conclusion to be drawn from the above discussion is that countries need their own basic research to sustain technological development. Personal links and mobility are vital in linking basic research and technological development. This, in turn, points to the importance of linking basic research to post-graduate training, ensuring that the latter is carried out in organisations at the forefront of their research field.

4.3 Measuring rates of return to basic research: the contributions of Mansfield

What is a rate of return to basic research? In considering this question, we first need to distinguish between private and social rates of return. Private rates of return to investment in basic research reflect those benefits which flow from the successful research project specifically to the investor in that project. Social rates of return to basic research, in contrast, are "the benefits which accrue to the whole society" (Smith, 1991, p. 4). In most cases, economists have attempted to measure the rate of return to basic research through its ability to lower costs. Lower costs are achieved both through reductions in the costs of inputs and through the ability to produce more outputs for the same inputs. "In either case, real national income rises. So when input costs fall as a result of an R&D project, this reduction is the 'social benefit' from an innovation. When the internal rate of return to a project is calculated using these social benefits as the returns, then we have the *social rate of return* to the R&D project" (*ibid.*, p. 4).

In his review of work on the measurement of returns to research, Smith identifies four reasons why it is particularly difficult to measure rates of return to publicly funded basic research:

(a) public research (and development) is often undertaken for non-economic reasons;

(b) public research often produces 'public goods' benefits - i.e. it is non-excludable and non-rival;

(c) methods for measuring outputs are weak where they concern public sector activities;

(d) the connections between basic research and innovation are "long-term, indirect, and unpredictable" (Smith, 1991, p. 2).

Given these problems, studies that purport to measure the rates of return to investment in basic research must be treated with some caution.

Until a few years ago, there had been few, if any, successful attempts to measure the rates of return to basic research.[8] Despite the problems, some recent efforts have nevertheless been made, the most important being those by Mansfield who has attempted

> to estimate the extent to which technological innovations in various industries have been based on recent academic research and the time lags between investment in recent academic research projects and the industrial utilisation of their findings. (Mansfield, 1991, p. 1)

His primary focus is on recent academic research - "that is, research occurring within fifteen years of the commercialisation of whatever innovation is being considered" (*ibid.*, p. 1) Using a sample of 75 major American firms in seven manufacturing industries (information processing, electrical equipment, chemicals, instruments, pharmaceuticals,

---

[8] As the authors of an authoritative US review noted, "Econometric approaches have been unsuccessful in establishing a return on federally funded R&D. Unlike the strong and consistently positive correlations found between privately financed R&D and productivity growth in the manufacturing industries, only weak and inconsistent correlations have been found for federally funded R&D" (OTA, 1986, p. 14).

metals and oil), Mansfield obtained information from company R&D executives concerning the

> proportion of the firm's new products and processes commercialised in 1975-85 that, according to these executives (and their staffs), could not have been developed (without substantial delay) in the absence of academic research carried out within 15 years of the first introduction of the innovation. (*ibid.*, p. 2)

The survey revealed that about 11 per cent of these firms' new products and about nine per cent of their new processes could not have been developed "without a substantial delay" in the absence of academic research. The importance of recent research was rated highest by the pharmaceutical industry and lowest by the oil sector.

What was the economic importance of those new products and processes? Starting from the figures on total sales in 1985 for each of the firms surveyed, Mansfield estimated the volume of sales of new products that could not have been commercialised "without a substantial delay" in the absence of academic research conducted over the specified period. The figure for the firms surveyed was equivalent to 3 per cent of overall sales. For new processes, the corresponding figure was 1 per cent of sales. Mansfield also estimated the value of new products or processes which were developed "with substantial aid" from recent research. The figures obtained here were 2.1 per cent of sales for new products and 1.6 per cent for new processes.

In order to measure the social rate of return to academic research, Mansfield suggests that it is necessary to know "what would have happened if the resources devoted to academic research were withdrawn - and not allowed to do the same or similar work elsewhere" (*ibid.*, p. 6). To calculate this, he makes a number of (rather heroic) assumptions:

- he measures the benefits of academic research simply over seven years, assuming (conservatively) that by the eighth year firms would have achieved this innovation regardless of academic research;
- the results of academic research carried out around the world between 1975 and 1979 (for which he obtains figures on the total funding) will have been incorporated in new products and processes commercialised in 1982-1985 in the United States;
- the new products and processes result in no social benefits other than those accruing to the innovator;
- half of the profits from the new products and processes that could not have been developed in the absence of academic research are credited to that research.

Mansfield's resulting estimate is that the social rate of return for academic research is 28 per cent. This figure represents "the present value of the stream of benefits associated with the research equal to costs. (In other words, it is the annual profit rate on society's investment in academic research.)" (*ibid.*, p. 10) Mansfield observes that, although this figure is high, it does not include:

(a) the social benefits to innovations based on academic research in all industries other than the seven in the survey;

(b) the increases in annual social benefits from innovations based on academic research after their first four years of commercialisation;

(c) the social benefits from innovations based on academic research findings that are commercialised more than 15 years after the findings or that are introduced by non-major firms.

Mansfield admits that his data are very approximate and contain sampling errors. Nevertheless, he concludes that in several industries, such as pharmaceuticals and instruments, the economic contribution of academic research to industrial innovation has been considerable. These findings have been widely quoted by scientists and research-funding agencies and have certainly been influential. However, a number of limitations should be noted.

(a) First, his estimate of the social rate of return is very sensitive to the time lag (a maximum of 15 years) assumed for the commercialisation of academic research. Yet often it may take far longer for the results of basic research to reach the marketplace through new products (CBO, 1993, p. 15).

(b) He did not count the benefits from academic research generated outside the United States.

(c) His approach does not capture more indirect benefits of basic research such as the development of skills and problem-solving abilities, nor the artefacts, instruments and tools used by industry that are ultimately derived from basic research, perhaps through an indirect or multi-link chain.

(d) He analysed the average, not the marginal, rate of return from academic research with the consequence that his findings cannot be readily translated into policy guidelines on the appropriate level of funding for basic research.[9]

(e) His sample of firms is biased towards basic research-using large firms in R&D-intensive industries.

(f) His approach is dependent upon the opinions of company R&D managers who may tend to rate their company's internal technical activities more highly than university basic research.

(g) R&D is only one part of a much larger process of production, development and marketing, and the level of expenditure required to bring a product to market is substantial. Whether the full cost of this has been taken into account by Mansfield is debatable.

The conclusion to be drawn from this section is that one can arrive at estimates of the rate of return to basic research, but only on the basis of a large number of questionable assumptions. Mansfield has carried this form of investigation furthest. His conclusion - that there is a very substantial rate of social return to basic research - is plausible (particularly as most of the limitations outlined above are likely to result in an under-estimate rather than an over-estimate of the benefits), but the exact figure he obtains must be treated with some caution. It would certainly help if similar studies were to be carried out in other countries to see if they yielded a comparable figure. This is one option that might be considered for the UK.

5.0 DIFFERENT TYPES OF BENEFIT FROM BASIC RESEARCH

The various forms of economic benefit from government-funded basic research can be classified into six broad categories:

---

[9] Indeed, almost all studies of the rates of return to investments in basic research carried out to date have measured only the average return on total investment. As a comprehensive US review on the subject concluded, they say little about "the marginal return that can be expected from the next incremental investment in basic research. In this sense, these studies offer little guidance for policy makers, other than by stressing the importance of investments in basic research in general." (OTA, 1986, p. 4)

1. increasing the stock of useful information;
2. new instrumentation and methodologies;
3. skilled graduates;
4. professional networks;
5. technological problem solving;
6. creation of new firms.

These different forms of benefit are, however, interconnected and mutually supporting; for example, the training of skilled graduates not only promotes the development of professional networks but also facilitates the transfer of new information and methodologies into industry. In what follows, we consider work carried out to analyse and assess each of these types of benefit.

5.1 Increasing the stock of information

The original justification for public funding of basic research was set out by Arrow and Nelson. A recent statement of that rationale is as follows:

> economically useful output of basic research is codified information, which has the property of a 'public good' in being costly to produce, and virtually costless to transfer, use and re-use. It is therefore economically efficient to make the results of basic research freely available to all potential users. But this reduces the incentive of private agents to fund it, since they cannot appropriate the economic benefits of its results: hence the need for public subsidy for basic research, the results of which are made public. (Pavitt, 1995a, p. 4)

New growth theory initially highlighted the 'public good' nature of basic research, stressing its non-rival and non-excludable nature (e.g. Romer, 1992); 'non-rival' means that one individual's or firm's knowledge will not reduce that possessed by others, and 'non-excludable' means that others cannot be excluded from obtaining the knowledge that the firm in question has. These two assumptions are sufficient to define 'publicness', as Romer and others have shown.

There is a significant and growing body of opinion that the traditional focus on the information component of scientific knowledge fundamentally underplays the person-embodied nature of knowledge. A large body of empirical work on the nature of knowledge has pointed to the importance of the tacit dimension of knowledge. Rosenberg argues that advocates of the information-based view tend to regard scientific knowledge

> as being 'on the shelf' and costlessly available to all comers once it has been produced. But this model is seriously flawed because it frequently requires a substantial research capability to understand, interpret and to appraise knowledge that has been placed upon the shelf - whether basic or applied. (Rosenberg, 1990, p. 171)

This can be seen as the equivalent for individuals of the 'absorptive capacity' of firms noted above. Individuals need to develop substantial skills and to expend considerable resources to understand codified knowledge. It is a labour-intensive process, involving extensive trial and error, effort and learning. Moreover, among individuals and organisations, there are wide variations in the ability to make sense of the codified knowledge available to them. The ability to understand codified knowledge requires organisations to maintain a substantial and often expensive research capability. Without this capability, organisations would be unable to interpret and derive value out of the growing body of codified knowledge. Faulkner and Senker (1995) suggest that codified knowledge is only capable of transmitting partial information, and the application of that information also requires personal interaction for the transmission of associated tacit knowledge and skills.[10] This may be particularly important in emerging technologies, and in fast-moving scientific fields. In the process of transferring knowledge, ambiguities abound. Personal, face-to-face interaction is often essential. Indeed, the physical movement of skilled individuals between organisations is generally the best (and perhaps often the only) way of enabling the transfer of many forms of knowledge that are imperfectly codified (Pavitt, 1995a).

Hicks (1995) suggests that the function of codified knowledge is largely to signal the presence of tacit knowledge and skills and thereby to facilitate their movement. Codified knowledge is very useful in this task precisely because it is so mobile. As the PACE study (discussed in following sections) found, publications are the most common source for learning about public research. Over 58 per cent of respondents cited publications as important, the highest score among the various methods surveyed (see Table 3 over). Publications were important in all industries surveyed and especially so in pharmaceuticals, basic metals, and glass, ceramics and concrete. However, economists who mistake this one visible and mobile component of knowledge for the whole thing fail to understand how much knowledge moves (or spills over).

Economists might counter that knowledge is a local public good - freely available to the community of specialists. Callon (1994) argues that this view entails a superficial analysis of the costs involved in using knowledge. Acquiring codified knowledge may indeed be relatively cheap in comparison to standard goods. However, the costs of *using* knowledge are considerable, whereas the costs of using a standard good are generally low. To use a piece of codified knowledge, one must acquire and maintain assets complementary to the codified knowledge such as skills and instruments. Furthermore, one needs to invest in applied research and development to create a useful product or process. The costs of acquiring and maintaining complementary assets and of development are substantial. Economists who view knowledge as a public good tend to count only the cost of the initial acquisition.

What does the combined tacit and codified nature of scientific knowledge mean for our understanding of the economic benefits of publicly funded basic research? The tacit component of knowledge substantially dilutes the information-based argument for the public subsidy of basic research put forward by Nelson and Arrow. Scientific research is not merely about the production of useful information, information that constitutes a direct input into the production process. Scientific research also involves a great deal of individual and organisational learning. It demands skills not only on the part of producers of the new information who publish scientific papers, but also skills on the part of receivers of that information. To think of basic research solely in terms of the production of information is to see only one part of the picture. This is where many of the studies of economic benefits of basic research are fundamentally flawed.

Recently, David and Foray have restated the argument that codified knowledge is crucial, claiming that the effect of pervasive information technology is to enhance the primacy of codified knowledge. They argue that scientific information can be considered as *codified knowledge* - that is, knowledge that has been transformed into a written form. Among the properties of codified knowledge are that it is:

---

[10] This finding is echoed by Zucker and Danby in their detailed work on academic stars and biotechnology: “Scientific discoveries vary in the degree to which others can be excluded from making use of them. Inherent in the discovery itself is a degree of ‘natural excludability’. If the techniques for replication involve much tacit knowledge and complexity and are not widely known prior to the discovery - as with the 1973 Cohen-Boyer discovery - then any scientist wishing to make use of the new knowledge must first acquire hands-on experience.” (Zucker and Danby, 1995, p.4)

TABLE 3 IMPORTANCE OF DIFFERENT SOURCES AND METHODS FOR LEARNING ABOUT PUBLIC RESEARCH

Source or Method	Percentage of Respondents Rating as Important	High Scoring Industries (Scores in Percentages)
Publications	58.4%	Pharmaceutical (90), Basic Metals (64), GCC (62), Utilities (61)
Informal Contacts	51.6%	Pharmaceutical (88), GCC (68), Utilities (67), Aerospace (60)
Hiring	44.4%	Pharmaceutical (66), Computers (56), Aerospace (52), Chemical (48)
Conferences	43.9%	Pharmaceutical (85), Utilities (56), Computers (56), Telecom (48)
Joint Research	39.5%	Aerospace (70), Basic Metals (68), Utilities (67), Pharmaceutical (51)
Contract Research	36.3%	Utilities (72), Pharmaceutical (51), Basic Metals (48), Plastics (46)
Temporary Exchanges	14.1%	Pharmaceuticals (27), Computers (22), Electrical (20), Basic Metals (20)

Note: Respondents in 16 industries were asked to rate the importance of each source or method on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage of respondents rating each source/method five or higher on that scale.

Source: Arundel et al. (1995)

(a) *non-rival* (as defined earlier in this section);

(b) *durable* - i.e. it does not lose its validity through use and re-use;

(c) *costly to protect* or to restrict access to it (Dasgupta and David, 1994, p. 494).

David and Foray argue that the digital revolution has intensified the movement towards the codification of knowledge, with advances in information technology having greatly increased our ability to codify knowledge. New electronic libraries and networks have made possible a dramatic increase in the stock of information available, both public and private, to would-be users. This greatly enlarged stock of information may bring about a "new epoch of 'library research' ", enhancing the productivity of researchers and expanding the laboratory beyond its spatial limits.

David and Foray claim that this process of codification is:

(a) bringing science and technology closer together and into tighter nodes of interaction;

(b) altering the institutional structure of the innovation process as access to science becomes more important across a wide variety of industries;

(c) leading to the formalisation of knowledge, thereby increasing the pace of new product and process development as the use of simulation speeds up the design process (David and Foray, 1995, p. 42).

The codification of knowledge makes possible a wider distribution of existing stocks of knowledge and the generation of variety and novelty through new combinations of existing stocks of knowledge. In this new environment, David and Foray argue that industries need to develop institutional structures which allow for "the dissemination of information regarding the stock of codes, technologies and programmes available, so that individual innovators can draw upon the work of other innovators" (*ibid.*, p. 44).

David and Foray, however, offer no empirical evidence of the increasing codification of knowledge, and others have claimed that it is tacit rather than codified knowledge that has been increasing. For example, in a study of the chemical, engineering, pharmaceutical and aerospace industries in the UK, Nightingale finds evidence that the use of computer simulations and information technology may be increasing the importance of tacit or person-embodied knowledge (Nightingale, 1996).[11] In the pharmaceutical industry, for instance, firms are moving towards the recruitment of those with post-doctoral experience rather than doctoral students in order to take advantage of their increased understanding of bio-chemical processes. Computer simulations, Nightingale argues, are not being used so much to codify knowledge but rather to deepen our understanding of chemical processes. They act as a complement, not an alternative to experimental research. They do not, by themselves, offer answers to technical problems, but instead tend to facilitate more experimental research (*ibid.*).

Economists who assume that basic research merely yields information are in danger of misunderstanding the nature of knowledge. One example of this can be seen in a paper by Adams (1990) which attempts to measure the relationship between academic science and productivity growth. Though earlier attempts to assess the impact of R&D on productivity growth have been fraught with difficulty, Adams claims that technical change can be linked back to the expansion of knowledge. Using a variety of statistical sources, such as the number of scientists employed and the number of papers published, he constructs a production function equation that includes a variable called the 'knowledge stock'. Adams admits the difficulties in measuring an economy's knowledge stock. Such

---

[11] It is possible that *both* codified and tacit knowledge may be increasing, since there is no reason why an increase in one must come at the expense of the other.

a measurement, he suggests, would have to take into account: (i) the fundamental character of knowledge pools; (ii) the heterogeneity of information; (iii) the repetitive use of science by industry; (iv) the interactive nature of the knowledge stock; and (v) the fact that the knowledge stock is time-specific since the rate of obsolescence of knowledge is not constant across fields or time (Adams, 1990, p. 678).

By counting of number of scientific papers (broken down by field) published in the United States, Adams constructs measures of the stock and flow of articles available to the knowledge pool from 1908 to 1982. He also measures the number of scientists and engineers available to the US economy from 1949 to 1984. He then constructs an estimate of the stock of knowledge for each of 18 industries based on the numbers of papers published and scientists employed. His figures indicate a decline in the 'intensity' of knowledge creation since the number of papers produced per researcher falls over time. Adams suggests that this decline in the productivity of scientists is related to the lack of research performed during the Second World War[12] (he assumes a 30-year lag for the take-up of scientific papers by industry) and speculates that 15 per cent of the economic slowdown of the 1970s can be explained by that earlier decline in the knowledge stock (*ibid.,* p. 699).

To sum up: the 'public good' argument has traditionally been used to provide a rationale for public funding of basic research. This assumes that basic research yields primarily codified knowledge which can then be freely used by others. David and Foray argue that information technology is resulting in a growing codification of scientific knowledge, but this has been challenged by Nightingale. Other work over the last ten years has highlighted the importance of tacit knowledge and skills, especially in emerging technologies and fast-moving scientific fields. Attempts to measure the economic benefits of the 'knowledge stock' generated by basic research are fraught with difficulty.

5.2 New instrumentation and methodologies

De Solla Price (1984) has pointed out that "A great deal of the actual work that goes on in all sorts of experimental laboratories consists in the discovery of new techniques for doing something or producing some new effect, then perfecting and extending the technique ..." (*ibid.,* p. 12) He suggested that the techniques of experimental science, which are not necessarily part of the knowledge system of science, can move on from being laboratory tools to much wider commercial applications. He provided many examples, including the discovery of X-rays, and the growing of single crystals which led to the invention of the transistor. These instruments and research techniques or methodologies may constitute one of the most significant forms of economic benefit to flow from publicly funded basic research.

Our review of the literature suggests that, as yet, no-one has attempted to make a direct measurement of the economic benefits of instrumentation and methodologies, or of their costs. Surveys of the relationship between science and industry tend not to consider the role of instrumentation and methodologies in any detail and to discount their importance. Furthermore, given the limited ability of industrial R&D managers to recognise the importance of earlier basic research and in particular the role of instrumentation and methodologies, it is likely that they will continue to remain undervalued in any future survey of such managers.

As regards the investment in such activities, De Solla Price (1984) could find little evidence on the percentage of research funding accounted for by experimental facilities. Nor could he find any data on "communication at the research front of the

---

[12] This is a somewhat questionable assumption, given all the research carried out during the Second World War on such topics as nuclear energy, radar, operations research and new drugs.

craft of experimental science" such as communication or mobility among technicians. Given there was some anecdotal evidence suggesting that new techniques are transferred very rapidly from one laboratory to another, including university to industry flows, he pointed to the need to devise indicators of national investment in laboratory instrumentation, methodologies and technical personnel. Collection of such data, however, would not solve the problem of finding techniques to measure the aggregate economic benefit of instrumentation or methodologies.

None of these methodological and empirical difficulties detract, however, from the importance of scientific instrumentation as a form of economic output from research. As one influential commentator has noted,

> the emergence and diffusion of new technologies of instrumentation ... are central and neglected consequences of university basic research. ... [The] eventual economic impact of basic research is commonly expressed through the medium of new instrumentation technologies and the life histories of these new technologies. (Rosenberg, 1992, p. 381)

Scientific instruments are the 'capital goods' of the scientific research industry, Rosenberg suggests. The conduct of research requires specific equipment for the "purposes of enhancing the ability to observe and measure specific categories of natural phenomena" (*ibid.*). Many of the instruments now in use began in basic research - in the attempt to "advance the frontier of scientific knowledge through an expansion of observational or experimental capabilities" (*ibid.*). Basic research has begot new instruments which have expanded observational and measurement techniques.

Across a whole range of scientific instruments, the original instrument was often designed for a specific problem in a particular speciality as a requirement of research in that speciality. After its initial development, the instrument diffused, eventually becoming useful in other areas of science, although often it required modification or redesign. "Similarly, scientific instruments that were designed to improve research capability on one set of problems have often turned out to have applications in scientific regions far from those where they originated" (*ibid.*). For example, in its early years the computer was primarily a research instrument and many recent advances in research capabilities have occurred by linking other new scientific instruments to the computer.[13]

There are two main diffusion paths for instruments. First, instruments have often moved from one scientific discipline to another. For example, Rosalind Franklin contributed to Crick and Watson's discovery of the 'double helix' structure of DNA by mastering the technique of making good X-ray diffraction pictures from very small and poorly crystallised organic molecules (Rosenberg, 1992, p. 383). Rosenberg sees this instrumentation flow as being particularly strong from physics to chemistry, as well as from physics and chemistry to biology, clinical medicine and ultimately to health-care delivery.[14] Here, Rosenberg cites spectroscopes, electron microscopy, X-ray crystallography, and nuclear resonance. Nuclear magnetic resonance, for example, was pioneered by physicists at Harvard and Stanford Universities who were trying to measure the magnetic moments of atomic nuclei - an innovation for which they received the Nobel Prize for physics. New instrumentation in one field often brings about increased collaboration across disciplines. In addition, new instrumentation has led to creation of

---

[13] Early pioneers of the computer such as H. Aiken, J. Atanasoff, K. Zuse, J. P. Eckert and J. W. Mauchly "were confronted by extremely tedious and time-consuming computational requirements in their research work, typically involving solutions to large systems of differential equations" (Rosenberg, 1992, p. 382).

[14] "The record clearly shows that most innovation in medical instrumentation since the turn of the century, even that of the past few decades, has come from the universities and medical schools and not from the medical device industry." (p. 99 in *Physics Through the 1990s* (National Academy Press, Washington, D.C., 1986), quoted in Rosenberg, 1992, p. 384).

entirely new fields, such as geophysics, computational physics and artificial intelligence. Often, the migration of particular instruments across fields depends on the movement of skilled researchers and students across disciplinary boundaries. Secondly, instruments developed in basic research have been transferred on a very extensive scale to industry. "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" (Rosenberg, 1992, p. 384). In many instances, scientific instruments have become indistinguishable from industrial capital goods. Rosenberg quotes the semiconductor industry as an example:

> Ion implantation originated as a technique of basic scientific research in the field of high energy particle physics. Its origins lay in the early work of particle physics which flowed from the recognition that magnetic and electric fields could be used to impart energy to particles. Methods of charging, accelerating and directing these ion beams were developed in order to elucidate theories of physics. As the frontier of very large-scale integration created a need for controlling the deposition of impurities on semiconductor devices with ever-higher degrees of precision, ion implantation techniques were transferred to the semiconductor industry. (*ibid.*, p. 385)

Other recent prominent examples of the transfer of instruments and techniques include lasers, recombinant DNA, the Internet and the World-Wide Web. Indeed, modern biotechnology could not have come into existence without the complementary developments in computers (in bio-informatics and the development of huge relational databases) and computer-aided design (in molecular modelling). These examples indicate that instruments and methodologies developed in the pursuit of scientific knowledge often have a direct impact on manufacturing processes, though their full impact may only be felt after a considerable time lag. Recent empirical studies of a range of industries have shown that instrumentation is becoming a dominant area of application of new technologies, even in supposedly 'low-tech' industries; moreover, they indicate a sharp rise in the patenting of instruments in some 'higher-tech' industries such as electronics (von Tunzelmann, 1995 and 1996).

Clearly, many instruments which originated in academic laboratories have been developed by firms and these firms have then made substantial improvements to the performance, versatility and cost of those instruments. There are strong and positive feedbacks between instruments manufactured by firms and science, as relatively cheap but high-performance instruments get channelled back into basic research, thereby increasing the research capabilities of scientists. There are also strong connections between users of scientific instruments and manufacturers (Von Hippel, 1988).

New instruments often require further research, sometimes of a more basic nature, to improve their performance, and these new lines of research, triggered by instrumentation, take on their own dynamic, assuming a significance independent of the initial needs of the new instrument. The first versions of new instruments are often clumsy or unpredictable; these limitations may then trigger intense research to overcome them. That research can, in turn, spur new scientific inquiries. In some cases, instrumentation effects may be so strong that they alter the pace of scientific advance as new instruments are transferred from discipline to discipline and from science to industry (Rosenberg, 1992, p. 388).

Rosenberg suggests it would be misleading to assume that developments in instrumentation would have occurred regardless of basic research at universities; often, the new instrumentation "arose precisely because university researchers were allowed to pursue fundamental questions that offered no apparent prospects of financial payoffs" (Rosenberg, 1992, p. 389). Basic research stimulated the "radical innovative initiatives that led, in many cases, to the eventual supplying of its own internal demand and, in the process, provided large external benefits as well" (*ibid*., p. 389).

Despite Rosenberg's challenge to researchers in science policy to discover the ways in which instrumentation stimulates economic benefit, there has been little empirical research on this other than a few case studies. Those studies highlight the key role of instrumentation, although they reveal that its importance varies considerably among scientific and technical fields. For example, Hicks (1992) found significant differences concerning the importance of instrumentation in two subfields of physics. Through interviews with scientists and an analysis of published papers in the subfields of spin-glass and superfluid helium three, she showed that in some cases instrumentation can be less critical to scientific advance than information or communication among scientists. In spin-glass, the scientists rely on "technology at the commercial state of the art" and it was "less often the case that research depended for success on transcending the commercial state of the art in components" (Hicks, 1992, p. 191). Her analysis showed that the most cited papers in spin-glass tended to be produced on "less than state-of-the-art equipment". Research on superfluid helium, on the other hand, involved "technologically sophisticated" instrumentation. "Substantial effort was expended in designing, building and debugging experimental equipment," (*ibid*., p. 196) The conclusions to be drawn here are that instrumentation is not always the principal factor in the advance of a scientific field, and having basic researchers who develop sophisticated instrumentation is no guarantee of a commercial spin-off. The only spin-off from these two areas came from spin-glass, and from spin-glass theory at that (*ibid*., p. 201). In short, Hicks research suggests that, although instrumentation can facilitate scientific advance and provide economic benefits from basic research, it does not do so uniformly in every scientific field.

Despite the difficulties in measuring the economic benefits of instrumentation, the PACE Report offers a snapshot of the importance of basic research instrumentation in technical advance. In the PACE survey, respondents were asked to rate the importance of different outputs of public research institutes and universities. Of the different outputs of public research (specialised knowledge, instrumentation, general knowledge from basic research, and prototypes), respondents rated instrumentation as the second most important output of basic research. Instrumentation is especially important in the pharmaceuticals, glass, ceramics and cement, electrical, and aerospace industries. Instrumentation was considered relatively unimportant in instruments (surprisingly), computers, and plastics industries. The low rating for instrumentation from these industries, especially computers, highlights the difficulties of surveys in measuring the benefits of basic research (see Table 4 over), especially as the actual empirical results alluded to above showed that patenting by such industries in this field was increasing both relatively and absolutely.

To conclude, instruments and techniques, prior to the work by de Solla Price, tended to be accorded less importance as both a source of scientific advance and as a form of economic benefit from basic research. Case studies by Rosenberg and others have highlighted that instruments and methodologies constitute an important economic benefit, although that importance varies across scientific fields, technologies and industrial sectors. It is, however, exceedingly difficult to arrive at any quantitative estimate of the magnitude of that economic benefit, not least as it can take several decades for it to be realised. Although access to state-of-the-art equipment is often a necessary condition for performing basic research, even in areas where instrumentation is not the main focus of the research, the development of instrumentational spin-off is almost as difficult to predict as any pay-off from basic research.

5.3 Skilled graduates

Numerous studies of the economic benefits of basic research have highlighted skilled graduates as one of the chief forms of economic benefit from basic research. Graduates entering industry come equipped with advanced levels of training, knowledge and

Table 4 Importance to Industry of the Different Outputs of Public Research

Form of output	Percentage of respondents rating as important	High scoring industries (scores in percentages)
Specialized knowledge	55.7%	Pharmaceutical (84), Utilities (64), Food (57), Aerospace (57)
Instrumention	35.2%	Pharmaceutical (49), GCC (45), Electrical (42), Aerospace (39)
General knowledge from basic research	32.2%	Pharmaceutical (76), Chemical (38), Computers (38), Instruments (36)
Prototypes	19.4%	Food (28), Pharmaceutical (27), Electrical (26), Basic Metals (24)

Note: Respondents in 16 industries were asked to rate the importance of each form of output on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage of respondents rating each form of output five or higher on that scale.

Source: Arundel et al. (1995)

expertise. (They are also ‘plugged into’ international networks of scientists and have experience of tackling complex problems, issues covered in the next two sections.) They often bring with them tacit skills - that is, skills which are person-embodied. These skills are generally difficult, and sometimes impossible, to pass on through written information or statements, such as scientific papers. They reside within individuals as a product of a personal learning process and as part of the set of tools and capabilities acquired unconsciously alongside that process. Among the most important of these skills are the acquisition and effective utilisation of knowledge:

> As far as companies are concerned, formal qualifications are ... evidence of researchers’ tacit ability to acquire and use knowledge in a meaningful way. This attitude of mind ... is a most important contribution to new product development. (Senker, 1995)

Graduates from basic research are able to “make use of recent information and to expand the resources at their command and hence gain access to a wider range of possible solutions to a specific problem” (Gibbons and Johnston, 1974, p. 239). Graduates trained in basic research may not have readily to hand the solutions to a particular problem, but they know where to set about seeking the kinds of information and skills necessary to solve the problem. Through their personal connections with fellow researchers in the field, they can muster the latest and best available scientific resources to tackle that problem (*ibid.*). Similarly, Lyall, in her analysis of the submissions made during the preparation of the 1993 White Paper on Science, Engineering and Technology, showed how strongly British industry (and in particular chemical and pharmaceutical companies) value the training benefits associated with basic research as well as its role in generating novel ideas (Lyall, 1993, p.41).

Some analysts have argued that formal training in underlying concepts and sophisticated technical skills of the sort provided by advanced training in basic research are indeed needed by industry:

> Academics may be able to teach what new industrial scientists need to know, without having their research be particularly relevant to industry. Basic scientific principles and research techniques may be highly important for a young scientist going on to industry to learn, even if the research being done by academics stands at some distance from what is going on in industry. (Nelson, 1987, p. 87)
>
> Industrial scientists and engineers almost always need training in basic scientific principles and research techniques of their field, and providing this training is a central function of universities. Current academic research in a field, however, may or may not be relevant to technical advance in industry, even if academic training is important. (Nelson and Levin, 1986)

In a study on the economic effects of ‘big science’, Irvine and Martin showed that the main economic benefits accruing to society from radio astronomy were achieved through the subsequent activities of former postgraduates (i.e. MSc and PhD students) who participated in the research programmes at the radio astronomy observatories. In their study, they reviewed the different forms of spin-offs from radio astronomy. As regards instrumentation and the benefits to equipment suppliers, Irvine and Martin concluded that “the level of technological spin-off has been rather limited” (Irvine and Martin, 1982, p. 113). Much more important were the economic benefits associated with the skills embodied in the postgraduates trained in radio astronomy who later moved on to other occupations. A survey of these former students revealed that their training in such tasks as the construction of receiver equipment, the development of computer programmes, and the devising of mathematical techniques for processing and analysing data was found to be extremely useful in their subsequent careers. About 30 per cent of those surveyed had at some stage occupied a post involving “research, design, and development” in industry (*ibid.*, p. 113). In terms of the number of working years, the radio astronomy graduates had spent substantial amounts of time in telecommunications, radar, computing and related areas (e.g. those dealing with wave-propagation problems).

The conclusion from this latter study and from the other work referred to above is that the funding of basic research, even in a very basic field like radio astronomy, does have substantial economic benefits, but those benefits are located more in the quality and skills of students rather than in the instrumentation developed or the scientific discoveries made in the field. In the case of 'big science' and probably most other areas of basic research as well, high quality graduates learn valuable skills that enable them to enter advanced technology fields and apply these techniques to the benefit of UK industry (*ibid.*, p. 115). It is therefore essential that basic research and graduate training continue to be conducted in the same institutions.

5.4 Professional networks

Many authors stress the importance of funding for basic research as an 'entry ticket' to personal and information networks of scientific research. Government funding provides a nation's institutions and individuals with the means to participate in, and interact with, the world-wide community of leading researchers. Yet despite the importance of public funding of basic researchers to enable them to carry out this networking function, no studies have apparently been carried out on the magnitude of the economic benefits derived from participating in these networks.

Recent research has pointed to the importance of networks in addition to the traditional view of research as a source of information. For example, the PACE study (described in the following section) revealed that informal contacts are one the most important methods for learning about research conducted in public institutes. Table 3 (p. 18) which summarises the results of the study shows that the different forms of network relations - for example, informal contacts and conferences - are highly rated. The costs of these various types of contact were judged to be low. Informal contacts and conferences were important sources for learning about the output of public research in pharmaceuticals, glass, ceramics, cement, and utilities industries.

Another relevant study here is that by Hicks (1995) who examined why companies publish research papers in refereed scientific journals. The first point to note is that certain companies now publish quite extensively. "A count of articles, reviews and notes indexed in the *Science Citation Index* showed that in 1989 certain large companies published upwards of 200 papers per year, with one or two reaching 500" (Hicks, 1995, p. 403). In 1991, companies participated in 8 per cent of UK scientific papers. "On average, between 1980-1989, companies produced 6 per cent of Dutch scientific output. In the USA in 1991, companies produced 9 per cent of science and engineering publications" (*ibid.*). Some companies are now among the highest cited institutions in the scientific community. For example, in biological sciences, nine corporations have figures for the average number of citations per paper that place them among the top 25 US universities, with two companies - Cetus and Genentech - earning more citations per paper than any of the top 25 universities.

Why do firms publish scientific papers? One reason is to access technical opportunities in the science base, including the recruitment of skilled graduates who also carry with them bodies of tacit knowledge. Because tacit knowledge and publications are intimately related, publishing helps to develop the credibility of the research carried out within the company. Public researchers share their information, or participate in barter exchanges, with researchers who have something to offer in return - namely, useful tacit knowledge. Researchers in firms who are active contributors to scientific research are therefore regarded as scientific peers because their publications signal that they have useful tacit knowledge to offer. In this way, publications act as the entry ticket to scientific networks (Hicks, 1995).[15]

The workings of these networks have been investigated by a number of researchers. These studies illustrate the enormous diversity in the relations between science and industry and the wide variation in their importance across sectors and technologies. Sharp, for example, argues that the success of government-funded programmes to stimulate networking and collaboration may depend upon the development phase of the scientific research involved. In her study of the Biotechnology Directorate's Protein Engineering Club, she found that the industrial members of the Club valued highly the contacts made in the early stages of this emerging technology which enabled them to identify the scientists, both in the UK and overseas, who were pioneers in its development. Five years later, when the science had advanced and matured, attempts to convert the Club into a LINK programme foundered on the unwillingness of companies to collaborate in their research. Only when the LINK rules were changed to accept one-to-one collaborations (i.e. between one university and one firm) did the new LINK programme move forward (Sharp, 1993). This suggests that collaborative programmes (and the knowledge gained through them) yield greater benefits in the early, emerging phase of a new technology when knowledge is scarce and essentially person-embodied.

Faulkner and Senker, in their book *Knowledge Frontiers*, analyse the nature of public-private sector linkages in three areas - biotechnology, engineering ceramics and parallel computing. They show that the linkages between public-sector research and industry are often informal and face-to-face. Good personal relationships between company and public-sector scientists are a key to successful collaboration between the two sectors. These personal interactions are crucial in building up the mutual trust and respect which often leads to long-term contractual relationships. Overly zealous government programmes attempting to create new interactions or 'forced marriages' between industry and public-sector research may undermine some of these informal connections, thereby (perversely) weakening the links between public sector research and industry rather than strengthening them (Faulkner and Senker, 1995).

The substantial and widespread publishing of scientific papers by companies raises interesting questions about the nature of public and private goods. Hicks points out that the boundary between public and private knowledge is often problematic. "Here, ... what seems private can be public and what seems public can have private components" (*ibid.*, p. 408). Companies can publish because they are generally able to police the public-private boundary. They can screen material about to be published to ensure that it does not contain information which might be patented or knowledge of the more private aspects of their technology.

There has been some recent theoretical work by sociologists of science on the importance of networks, work which leads to a new justification for public funding of basic research. The starting point is that the concept of the 'public good' nature of scientific knowledge is flawed. As Callon has pointed out, the notion of a public good implies an object with intrinsic properties that determine its ability to become a marketable product for the purposes of commercial transactions. The public goods argument suggests that the results of basic research are difficult to appropriate, non-rival, durable and uncertain. Callon takes issue with each of these so-called intrinsic properties of science and concludes that scientific knowledge does not constitute a public good according to the usual definitions employed in economic theory (Callon, 1994).

---

[15] It would therefore be wrong to conclude that, because firms are engaging in public research, the need for public funding is declining. This would imply that public and private funding of research are substitutes for one another. The analysis by Rosenberg, Hicks and others shows that they are actually complementary, with the published research of companies representing the cost of admission to the international basic research community. Consequently, the way to interpret the growing industrial expenditure on research is that companies increasingly need access to public basic research.

In place of the ‘public good’ defence of science, he proposes that public support for basic research should be considered as an investment in network reconfiguration and renewal. Public funding for science generates new combinations of organisational and individual relations, opening up alternative forms of co-operation and mechanisms of interaction. The tendency in the market place is to ‘use up’ the available sources of technological variety, creating irreversibility and convergence and locking us in to certain technological options. Examples include the QWERTY keyboard, the VHS video-recorder and the petrol-driven automobile. Research creates new options. The government, by funding research, keeps generating new sources of technological opportunity, countering the economic forces which tend to drive us to a position where we have only one option.

Callon poses this argument not so much in term of ‘knowledge’ or ‘information’, but in terms of networks that include instruments, devices and papers as well as people and organisations. He therefore expresses his recommendation as a call for governments to support greater diversity in those networks; publicly funded basic research is required to create new forms of social relations, counteracting the tendency within industry to ‘consume’ the sources of new ideas and research. Through public subsidy, government can promote novel approaches to addressing and resolving technical problems by expanding the variety of scientific options available to firms (*ibid.*, p. 412). This may, however, then pose challenges for government research institutions which tend to reflect or embody earlier ‘sets’ of knowledge. For example, in their study of biotechnology and the UK Research Councils, Balmer and Sharp (1993) showed how the multidisciplinary new technology challenged the old institutional boundaries, causing fracture, breakdown and eventually reformation around new institutional forms.

In summary, the provision of access to professional networks is an essential aspect of basic research, both in terms of enabling basic researchers to keep up with world science but also in providing others with a means to access those networks and thereby benefit from basic research. This is revealed in case studies of university-industry links, and in studies based on indicators (e.g. numbers of scientific papers) combined with interviews. Theoretical work by sociologists of science confirms the importance of networks, and suggests a new rationale for the public funding of basic research in terms of creating new interactions, networks and hence new technological options. This links in with the conclusion of those who conducted the Yale survey of industrial R&D managers (described in Section 5.5 below) that “The set of technological opportunities in a given industry is one of the fundamental determinants of technical advance in that line of business” (Klevorick *et al.*, 1995, p.185).

5.5 Technological problem solving

In the broadest sense, basic research contributes to the economy by helping practitioners solve complex technological problems. A recent analysis shows that, in the world’s largest firms accounting for most of measured R&D activities, products and firms are ‘multi-technology’: in other words, their products and their skills encompass a wide and increasing range of technologies (Granstrand *et al.* , 1996; von Tunzelmann, 1996), each of which must be mastered and integrated into often complex products and production systems. Given the localised nature of the linkages between basic research and application, the national basic research infrastructure needs to provide a wide range of skills and knowledge.

The various categories of engineering knowledge are shown in Table 5 together with the means by which they can be generated. The three categories which can be transferred directly (i.e. in the form of codified knowledge) from basic research to application are transfers from science (theoretical tools and quantitative data), invention (fundamental design concept) and theoretical engineering research (to a range of categories). Experimental engineering research may also be transferred, but much of

TABLE 5 SOURCES OF DIFFERENT CATEGORIES OF ENGINEERING KNOWLEDGE

	Knowledge categories					
Knowledge generating activities	Fundamental design concept	Criteria and specifications	Theoretical tools	Quantitative data	Practical considerations	Design instrumentalities
Transfer from science			X	X		
Invention	X					
Theoretical engineering research	X	X	X	X		X
Experimental engineering research	X	X	X	X		X
Design practice		X			X	X
Production				X	X	X
Direct trial (including operation)	X	X	X	X	X	X

Source: Vincenti (1990)

this tends to be undertaken in firms themselves, together with design practice, production, and direct trial. The contributions of basic research to these latter activities are largely indirect, through the provision of trained problem-solvers, instruments and techniques, and background knowledge.

Substantial progress has recently been made in tracing the direct (i.e. codified) contribution of basic research to technological knowledge and know-how, through various bibliometric indicators, such as patent citations to scientific papers, and scientific papers published by business firms, either alone or collaboration with others. In the US (and probably elsewhere), the results show a skewed picture, with about half the linkages from basic research into the chemical industry and between 20 and 30 per cent into electrical and electronics products. In contrast, less than 10 per cent of the measured linkages are into non-electrical machinery, automobiles and aerospace, sectors which together account for nearly 40 per cent of all development expenditures by US manufacturing, and for more than 50 per cent of employed scientists and engineers (Pavitt, 1995b). In addition, the aggregate impact of basic research, as measured through patent citations to scientific papers, is much less than its share of total R&D expenditures. Hence, at first sight, basic research would not appear to be a particularly efficient investment for technological change. However, there is strong evidence to suggest that the indirect benefits to technology of basic research outweigh the direct ones, although the balance between the two varies considerably across sectors.

The most systematic analysis so far of both the direct and the indirect benefits of basic research emerges from the Yale Survey, the main findings of which are summarised in Table 6. It was based on a questionnaire survey of 650 US industrial R&D directors covering 130 industries. One of the main findings was that industries where the general relevance of science (as a pool of knowledge) was judged to be very important in contributing to recent technological advances were approximately three times as numerous as those where specific university research results were judged to be very important (compare the fourth and the second columns). The authors interpret this as follows:

> The data suggest systematic differences between the role of science as a pool of knowledge ... and the role of ... university research. Overall, university-based research in a field is reported as much less important to recent technological advance than is the overall body of science in that field. ... A total of 74 industries (more than half the sample) rated the relevance of chemistry as ... 5 or higher, but only in 19 lines of business did university research in chemistry receive that high a mean score. Similarly, in physics, computer science, materials science, and metallurgy, the generic relevance of the field to industrial technologies is perceived to be much greater than the specific relevance of university research.
>
> In general, 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 the 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. In contrast, to the extent that new research in basic science is relevant to industrial technology, it is likely to be as an addition to the broad knowledge base rather than directly useful results. ...
>
> This 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

Table 6 The Relevance to Industrial Technology of (i) University Research and (ii) Knowledge of the Science

Scientific field	Number of industries rating *university research* as important, and high scoring industries		Number of industries rating *knowledge of the science* as important, and *high scoring industries*	
Biology	12	Animal Feed, Drugs, Processed Fruits/vegs.	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 Prods.	16	Pesticides, Animal Feed, Fertilisers, Food Prods.
Applied Maths/O.R.	16	Meat Prods., Logging/Sawmills	32	Guided Missiles, Aluminium Smelting, Motor Vehicles
Computer Science	34	Optical Instr., Logging/Sawmills, Paper Machinery	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		na
Electrical Engineering	22	Semiconductors, Scientific Instruments		na
Mechanical Engineering	28	Hand Tools, Specialised Industrial Machinery		na

Note: Respondents in the 130 industries were asked to rate the importance of each scientific field on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage rating each scientific field five or higher on that scale.

Source: Klevorick et al. (1995)

> 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.
>
> ...biology is an exception to the rule ... almost all the industries that value the contribution of the biological science generically, small as that number is, also value university-based contributions in that field. This reflects the fact that a very substantial fraction of agricultural and medical research is conducted in universities. Furthermore, ... those industries with technologies based on the biological sciences seem to be fed by new scientific developments to an unusually great degree. (Klevorick *et al.*, 1995, pp. 196-7)

In addition to the obvious and well-known linkages between scientific fields and industrial sectors (e.g. biology with food and drugs, physics with electronics, metallurgy with metals), some of the linkages shown in Table 6 are more surprising and potentially more revealing. In particular, there are the strong linkages between the motor vehicle sector and knowledge of the fields of mathematics (pure and applied) and computer science. According to Brooks:

> Theoretical prediction, modelling and simulation of large systems, often accompanied by measurement and empirical testing of subsystems and components, has increasingly substituted for full scale empirical testing of complete systems, and this requires design tools and analytical methods grounded in phenomenological understanding. (Brooks, 1994, p.480)

Thus, in industries (like motor vehicles) dominated by complex products or production systems, university research (normally in engineering departments) provides design tools, analytical methods and related skills that are used by firms themselves in their own extensive design, evaluation and testing activities. There is an important contrast here between industries based on chemistry and biology where there is often direct use of new chemical entities and techniques discovered in science, and the engineering-based industries where the process is more round-about. In the latter, new tools, pioneered in university laboratories, will be borrowed and adapted on-the job, with knowledge becoming increasingly tacit, learned by experience and passed on by word of mouth. As such, the origin of that knowledge tends to become increasingly obscured, and the benefits - for example, in terms of savings in the time and cost of testing expensive prototypes and pilot plants - may not be seen as linked to the original basic research.

An important source of information on the direct and indirect benefits of basic research in Europe is the recently released PACE Report which was funded by the European Commission. The survey involved a mailed questionnaire of the European Union's largest manufacturing and industrial firms. The survey

> asked about the goals of innovation, external sources of information, public research, methods to protect innovation with a focus on patents, government programmes to support innovation, and barriers to profiting from innovation. (Arundel *et al.*. 1995, p. i)

The results are based on 640 responses, including 111 firms in the UK.[16] The survey grouped respondents into 16 sectors.[17] Firms were selected on the basis of their legal

---

[16] The response rate was 56 per cent, slightly higher than in the Yale survey.

[17] The sectors include food, petroleum, chemicals, rubber and plastics, glass/ceramics/cement, basic metals, fabricated metals, aerospace, non-electrical machinery, computers, electrical equipment, instruments, automobiles, utilities, telecommunications equipment, and pharmaceuticals.

TABLE 7 IMPORTANCE OF DIFFERENT SOURCES OF TECHNICAL KNOWLEDGE

Source of technical knowledge	Percentage of respondents rating as important
Technical analysis of competitor's products	46.9
Independent suppliers	37.1
Affiliated firms	37
Independent customers	36.6
Joint ventures	32.7
Public research institutes	31.5

Note: respondents in the firms were asked to rate the importance of each knowledge source on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage of respondents rating each knowledge source five or higher on that scale.

Source: Arundel et al. (1995)

status within the European Community and their manufacturing or industrial activities. Only firms performing formal R&D and with sales above 1.5 billion ECUs were chosen. The questionnaire was sent to R&D managers in separate units of each large firm. The questionnaire itself was made up of 20 questions and conducted by the Maastricht Economic Research Institute on Innovation and Technology (MERIT)

The results of the PACE survey broadly confirm those of the early Yale Study (Levin *et al.*, 1987; Klevorick *et al.*, 1995). The links between industry, on the one hand, and basic research and the sources of technical knowledge, on the other, vary appreciably across sectors and nations. The survey found that technical analysis of competitor's products is the most important source of external technical knowledge for firms. Technical knowledge garnered from independent suppliers, affiliated firms, and independent customers followed in importance. The different sources of technical knowledge are summarised in Table 7. Public research institutes and universities were rated as important by almost 32 per cent of respondents. However, there are wide variations across industrial sectors, with public research being most important in utilities, pharmaceuticals, aerospace and food, and far less so in fabricated metals, plastics and telecommunication equipment (see Table 8 over).

The survey also showed that the importance of domestic research over foreign sources of knowledge varies by country. UK respondents stated that they valued domestic public research higher than foreign sources. As the PACE Report notes:

> Domestic public research is substantially more important to respondents than foreign sources, suggesting that the public research infrastructure is one of the most important national assets for supporting innovation. (Arundel *et al.*, 1995, p. ii)

The UK respondents stressed the importance of basic research over more applied areas of research. They also indicated that they found information and government technical assistance programmes the most helpful of the different forms of programmes surveyed (subsidies, procurement, public research, patent searches, information and technical assistance, R&D co-operation and information gathering abroad) (*ibid.*, p.68).

TABLE 8 USE BY INDUSTRY OF PUBLIC RESEARCH INSTITUTES AS SOURCES OF TECHNICAL KNOWLEDGE

Industry	Percentage of respondents rating as important
Utilities	69.4
Pharmaceuticals	53.0
Aerospace	43.5
Food	35.1
Automotive	30.1
Instruments	28.6
Electrical	28.2
Basic metals	28.0
Computers	27.3
Chemical	25.9
Machinery	25.3
Petroleum	23.1
GCC	21.4
Telecom	20.0
Plastics	12.5
Fabricated metals	10.8

Note: respondents in the firms were asked to rate the importance of each knowledge source on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage of respondents rating each knowledge source five or higher on that scale.

Source: Arundel et al. (1995)

As in the earlier Yale study, R&D managers were questioned about different research fields. Managers were asked to rate the fields in terms of the importance of publicly funded research over the past ten years to their firms' technological base. Given the short time-horizon referred to in the question (ten years), the results do not perhaps reveal the full benefits of basic research. The PACE survey does show that the slightly more applied areas like material sciences (rated as important by 47 per cent of respondents), computer sciences (34 per cent) and mechanical engineering (34 per cent), are the most important part of publicly funded research to the firms. Of the more basic fields, chemistry was rated comparatively highly at 29 per cent, some way ahead of physics (19 per cent), biology (18 per cent), and mathematics (9 per cent). The results, which are summarised in Table 9, show that the pharmaceutical industry is dependent upon chemistry, biology, and medical research, whereas the computer industry is dependent upon physics and mathematics. Of all 13 different industrial sectors, computers gave the highest rating to the more basic fields, followed by pharmaceuticals, aerospace and utilities.

TABLE 9 IMPORTANCE TO TECHNOLOGICAL BASE OF PUBLICLY FUNDED RESEARCH IN THE PAST TEN YEARS

Fields	Percentage of respondents rating as important	High scoring industries (scores in percentages)
Material Sciences	47.0	Aerospace (77), Basic Metals (76), Electrical (72), GCC (63)
Computer Sciences	34.4	Aerospace (60), Telecom (56), Automotive (47), Computers (47), Electrical (47)
Mechanical Engineering	33.7	Automotive (64), Aerospace (64), Utilities (53), Computers (47)
Electrical Engineering	33.0	Computers (78), Aerospace (73), Telecom (70), Electrical (56)
Chemistry	29.0	Pharmaceutical (78), Petroleum (52), Chemical (46), , Computers (33)
Chemical Engineering	28.7	Petroleum (60), Pharmaceutical (55), Chemical (46), Plastics (42)
Physics	19.2	Computers (64), Basic Metals (33), Plastics (25), GCC (25)
Biology	18.4	Pharmaceutical (71), Food (33), Petroleum (18), Chemical (17)
Medical	14.7	Pharmaceutical (85), Instruments (29), Computers (27), Food (15)
Mathematics	9.3	Computers (25), Aerospace (20), Automotive (20), GCC (13)

Note: Respondents in 16 industries were asked to rate the importance of publicly funded research on a seven-point scale (where 1 = not important and 7 = very important). The figures indicate the percentage of respondents rating publicly funded research five or higher on that scale.

Source: Arundel et al. (1995)

From the above discussion, we can conclude that the contributions of basic research to technological problem-solving are many, often indirect and roundabout, and highly variable across fields of knowledge and sectors of application. Simple models, generalisations and policy prescriptions for basic research are therefore likely to be misleading and even dangerous. Decentralisation, pluralism and experimentation are more likely to be efficient in generating benefits in terms of technological problem-solving of the type described here.

5.6 Creation of new firms

The final form of economic benefit from government-funded basic research to be considered here is the creation of new firms.[18] Overall, the evidence is mixed as to whether new firms have been created on a significant scale as a result of the funding of basic research. Work on this topic has been mainly based on case studies of particular universities[19] and fields of science. In a review, Stankiewicz (1994) found little convincing evidence of major benefits from academic research in terms of generating spin-off companies.[20] While it is certainly true that some universities are surrounded by a substantial number of firms, the growth rates of these companies is often low.[21] All too frequently,

> 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. (Stankiewicz, 1994, p. 101)

Research in the United States also reveals rather mixed evidence as to whether funding for basic research in universities leads to firm growth. In the electronic equipment sector, the correlation between university research and firm birth[22] is positive and statistically significant, while in instruments (surprisingly) the relationship is statistically insignificant (Bania, Eberts and Fogarty, 1993). In Australia, many of the leading companies in the scientific and medical instruments sector started out by commercialising public-sector research. For example, the second largest producer of spectrophotometers in the world, Varian Techtron Pty Ltd, has drawn upon and exploited the results of fundamental research carried out in CSIRO. Likewise, the success of Australia's leading medical equipment company is based on cochlear implant technology developed by the University of Melbourne (Prime Minister's Science Council, 1991; Van der Ven and Garud, 1991).

In biotechnology, Zucker and Danby found a strong correlation between 'star' bioscientists (those with over 40 gene sequence discoveries or 20 articles to their name) and the foundation of new biotechnology firms. They suggest that in the early phases of discovery, knowledge (for example, of recombinant DNA methodologies) is limited to those few who have been involved in the basic research experiments. Only by linking these scientists with commercial structures is diffusion (through commercialisation) possible. Zucker and Danby conclude that:

> star scientists embodying the breakthrough technology are the 'gold deposits' around which new firms are created or existing firms are transformed ...,

---

[18] To some extent, this type of benefit overlaps with the first five in that it offers an institutional mechanism through which those five forms of benefit may be realised. However, there is a relatively distinct literature on the creation of new firms so it is discussed separately here.

[19] For example, Segal, Quince and Wicksteed (1985) studied the creation and evolution of small firms located around Cambridge University.

[20] Autio (1995) has also reviewed the impact of new technology-based firms and comes to a similar conclusion to Stankiewicz.

[21] See also Massey *et al.* (1992).

[22] The corresponding issue of firms 'deaths' was, however, ignored.

> that firms which work with stars are likely to be more successful than other firms, and that - although access to stars is less essential when the new techniques have diffused widely - once the technology has been commercialised in specific locals, the internal dynamics of agglomeration keep it there. (Zucker and Danby, 1995, pp. 14-15)

Interestingly, the process appears to be of mutual benefit; those scientists with a commercial link also prove to be more productive in their academic research role (*ibid.*). One of the most notable examples of this occurred in the establishment of Genentech. In 1973, Herbert Boyer and Stanley Cohen, researchers at the University of California and Stanford University, discovered that DNA could be cut, recombined and inserted into a foreign bacteria which would then express a new gene - the techniques now known as genetic engineering. In 1976, Boyer set up Genentech, the first company to exploit recombinant technology. Its example was followed by a host of new biotechnology firms in the US, often with academic founders, because the genetic engineering skills needed to commercialise biotechnology were scarce and mainly restricted to those who had been doing research in universities and research institutes (Kenney, 1986). By 1991 there were approximately 750 new biotechnology firms in the US.

In Europe, such firms, of which Britain has the largest population (approximately 140), generally cluster in areas of academic excellence (Ernst & Young, 1994). Many of these firms have strong university links, but, in the UK, most have industrial, not academic founders (Oakey *et al.*, 1990). This is despite the fact that, according to Zucker and Danby, Britain has more ‘star scientists’ in molecular biology than any other European country. Most of these are not tied to new biotechnology companies and indeed a significant number of them emigrated to the United States. All of this suggests that the incentives present in the US which encourage academics to engage in entrepreneurial activity and to set up spin-off companies are less strong in the UK (Zucker and Danby, 1995, pp. 15-16).[23]

In summary, this evidence indicates that one cannot generalise about the benefits of basic research for new-firm creation. The “pipeline between university research and local commercialisation, as measured by a higher start-up rate of new firms, has substantial leaks” (Bania, Eberts and Fogarty, 1993, p. 765) Although there are substantial links and interactions between local industries and universities, it is not always the case that government-funded basic research leads to the formation of new firms. Claiming the creation of new firms as a benefit of publicly funded basic research has yet to be empirically validated, notwithstanding the few prominent examples identified.

6.0 BASIC RESEARCH IN THE UNITED KINGDOM

In this section, we first consider how companies in the UK make use of basic research, drawing upon the results of extensive case studies by two of the co-authors (Senker and Sharp) and their collaborators. We then discuss the relationship between basic research and UK comparative advantage. This includes looking in detail at the case of the chemical and pharmaceutical industries. Lastly, we examine the investment by foreign companies in R&D in the United Kingdom and the investment by European companies in R&D in the United States.

6.1 How companies in the UK use basic research

How exactly do firms in the UK make use of basic research? Which of the various forms of benefit from basic research discussed in Section 5 are most important for firms in

---

[23] It is significant that several of the ‘stars’ of US biotechnology were immigrants, with the UK being the prime source (Zucker and Danby, 1995, p.16).

different sectors? A recent study by Faulkner and Senker throws light on the various ways in which basic research supports industrial innovation in the UK. They investigated industrial linkages with publicly funded basic research in three promising fields of advanced technology: pharmaceutical biotechnology, advanced engineering ceramics and parallel computing. They focused on emerging technologies, where firms are still developing their knowledge base, because external sources of knowledge were thought to be significant to firms in these areas, and therefore the associated linkages would be more apparent. The study was concerned with research links from the company's perspective, and investigated both linkage activity and the knowledge which flowed through these links. Industrial researchers in all technologies reported that they use knowledge from a wide range of disciplinary fields. However, companies in the three technologies also use publicly funded basic research in different ways and for different purposes. While pharmaceutical companies are most interested in keeping up with the fast-moving research frontier, ceramics companies often use linkages with basic researchers to gain access to specialist equipment and related expertise to analyse new materials; in parallel computing, basic researchers represent sophisticated users of prototypes who can provide valuable test data and feedback on system performance (Faulkner and Senker, 1995).

The main finding to emerge from this study of three emerging technologies is the central importance to industry of the new knowledge emanating from basic research carried out in academic and government laboratories. For all the companies studied, it is evident that publicly funded basic research contributes most to innovation by training qualified scientists and engineers, and by being a potent source of new knowledge. This knowledge underpins industry's R&D programmes and, occasionally, offers new opportunities for exploitation. Industrial researchers gain knowledge and assistance from basic researchers in the public sector by reading journal articles, as well as by personal contacts. These two channels provide complementary types of knowledge. All the company researchers interviewed read the literature in order to keep up with the latest developments, but also find it important to supplement their reading with discussions of issues arising from the literature, often about methods and applications. Companies in all three technologies use a wide variety of formal and informal arrangements to access publicly funded basic research and these links contribute to innovative R&D in two distinct ways:

(a) as a source of new knowledge in specialist fields of science and engineering - it is vital that companies engaged in innovative R&D keep up with developments at the leading edge of research and gain the necessary underpinning knowledge;

(b) as a source of practical help and assistance, often in response to specific problems, and frequently in the area of experimental methodologies and research instrumentation, for example in interpreting results from test equipment.

Moreover, the study found that direct material inputs from publicly funded basic research to new product ideas or product development were minimal, contradicting the widespread belief that the main output of publicly funded research is inventions which can be transferred or spun-out for exploitation in the private sector (*ibid.*).

Linkages with publicly funded basic research should be seen in context: in all three technologies, internal R&D is the primary source of science and technology inputs to innovation. Even in new technologies, firms rely heavily upon in-house knowledge and efforts. Linkages with external research are no substitute for internal capability because, in order fully to understand and utilise knowledge generated outside, companies must have some relevant expertise of their own. Sometimes a linkage with public sector research institutions acts as a stepping stone to building up capability in a new field, but any subsequent product development takes place primarily in-house (*ibid.*).

In brief, the picture that emerges is one of industrial R&D integrating diverse inputs from both internal and external sources. Basic research carried out in university and other public sector laboratories is central, contributing much of the more general and formal knowledge through the education of scientists and engineers and through the literature. However, the findings confirm the importance to innovation of the specific and tacit knowledge and skills which build up cumulatively 'on the job' and then move with people from job to job or get transferred through personal contacts - including contacts in public sector research. The study demonstrates that the contribution made by public sector research to industry is largely made up of small and 'invisible' flows, the cumulative effect of which is very significant. Its findings indicate some of the difficulties to be surmounted in assessing the relationship between publicly funded basic research and economic performance (*ibid.*).

One specific issue that we were asked to address here is the extent to which UK businesses are aware of publicly funded basic research and its outcomes in areas of science relevant to their businesses and, where they are, whether the information available to them about publicly funded research in the UK is better than information about equivalent research being funded abroad. On this, there is relatively little literature. However, we can compare the findings from the SPRU study of technology foresight activities in eight overseas countries (Martin and Irvine, 1989) with those from the SPRU review of foresight in the UK a few years later (Martin, 1993). In these, a number of science-based companies were questioned about the approach they adopted to monitoring basic research around the world. The overall impression was that Japanese companies generally had the most systematic approach to scientific intelligence gathering, followed by the United States and Germany, with the UK some way behind. However, there are obviously individual exceptions, with three or four UK companies being more advanced in this respect (*ibid.*). These include some of those that have begun to establish research laboratories overseas.

6.2 Basic research and UK competitiveness

To what extent is basic research a significant factor in UK industrial competitiveness and economic performance? For well over a century, there have been those who claimed that deficiencies in research have been significant contributors to the relative decline of the UK, from its industrial pre-eminence in the middle of the nineteenth century (e.g. Jevons, 1866). Others have argued that such 'decline' occurred despite a continuing strength in basic research, as reflected, for instance, in the prominence of British scientists among Nobel prize winners (at least until recently). To the extent that there were problems, there have been accusations from both sides over whether science/academia or industry was more to blame. The most detailed historical investigation, by Sanderson (1972), concluded that, over the period 1850-1970, British universities produced sufficient researchers to meet the demands of British industry under most conditions, with the exception of some smaller 'niche' areas of science where shortages in the supply of skilled researchers could sometimes be observed. It is true that there are certain senior industrialists who believe that the training offered by UK universities may not be an ideal preparation for practical work in industry. On the other hand, a detailed study of the evidence submitted by industrialists at the time that William Waldegrave was preparing the White Paper on Science, Engineering and Technology concluded that the majority did not want universities to shift their research towards more applied work; rather, they should continue to focus on the basic research at which they excel (Lyall, 1993).

What is the picture at the level of individual sectors? In the case of the chemical and pharmaceutical sectors, the UK science base is still fairly strong in world terms (as reflected in publications and citations), while the industrial companies also have a good record in terms of growth and market share. As we describe in more detail in Section 6.3 below, the links between basic research and industry are often relatively simple and direct in these sectors. In other advanced technology industries like electronics, UK firms seem to have performed less well in international terms. Here, the science base may not be quite as strong either as it was in the past or in comparison with biological and life sciences. However, it is no weaker than the corresponding science base in other countries where electronics companies have performed with much greater success. The key issue here is not so much the relative strength of the UK science base, but the form of interaction between science and industry. Whereas a new chemical entity - or a genome sequence - once known can be replicated with little difficulty, any product that is essentially 'engineered', be it a semi-conductor or an aeroplane, embodies much tacit knowledge in its fashioning. Taking it to bits - or reverse engineering - may reveal some of this knowledge but by no means all. Furthermore, unlike the simple and direct form of interaction between basic research and chemicals or pharmaceuticals companies, more complicated multi-chain links are often involved here. An advance, say, in physics may first be transferred to another field (e.g. electrical engineering) and may then move through several other applied fields before eventually being taken up in industry. Whether British companies, subject as they are to delivering short-term profits, have the patience and the long-term investment funds to develop and manage these multi-chain exploitation routes effectively is open to question.

6.3 The chemical and pharmaceutical industries - a special case?

The chemical and pharmaceutical industries provide an excellent illustration of how close interaction with the science base helps to promote a virtuous cycle of innovation. The chemical industry (of which the pharmaceutical industry has been an important branch) emerged in the late nineteenth century to exploit the discoveries of German academics. It was the first truly science-based industry and Bayer, one of the largest German firms, was the first to establish an in-house R&D laboratory. The tradition spread rapidly and by the beginning of this century most of the large chemical firms had established laboratories. It was from these that the next wave of discoveries based on hydro-carbon chemistry - synthetic rubber, polyurethane, polyethylene, polystyrene, nylon and so on - emerged in the 1920s and 1930s (Freeman, 1963; Jewkes *et al.*, 1958).

Research has shown that this in-house technological strength was complemented by many external links to sources of scientific and technological information, of which basic research in universities was of prime importance (NSF, 1973). The web of linkages was extensive and complex, from professorial appointments to company boards to 'old boy' networks based on graduate recruitment. By these means, the companies kept abreast of developments in basic research coming mainly during the inter-war years from European universities (Freeman, 1963). In this respect, the R&D laboratories of these companies provided the mechanism for locating and assimilating new ideas which could add value to the companies' product portfolios.

The importance of the in-house laboratory to the innovative tradition of the chemical industry emerged as one of the main findings of Project SAPPHO undertaken by SPRU in the 1970s (Rothwell, 1977). Achilladelis and his colleagues subsequently extended the analysis in a series of detailed studies of innovations in the industry, all of which highlight how, given a strong innovative tradition within a firm, success breeds success (Achilladelis *et al.*, 1987; 1990; 1993) Skills and competencies generated in research, production and marketing in one major breakthrough breed confidence and generate profits which facilitate further innovations.

Gambardella, in his study of the pharmaceutical industry, remarks on the same phenomenon. In particular, he singles out the US pharmaceutical company, Merck (which has topped the league table for innovative drug discovery since the early 1980s) for its research tradition, stressing the importance in that tradition of its linkages to basic research:

> Although a public good, science is not a free good. Internal scientific

> capabilities are central for taking advantage of the public good. Firms like Merck and Eli Lilly pay systematic attention to scientific research and run their own research laboratories like academic departments. They have been more effective than their rivals in taking advantage of new scientific ideas and in the 1980s showed notable innovation and market performance. (Gambardella, 1995, p. 103)

However brilliant Merck's scientists, they, like their German predecessors in I G Farben, rely on the cross-fertilisation of ideas which derives from an extensive network of linkages with basic research in universities. Gambardella uses historical data series from the US pharmaceutical industry to test a series of hypotheses. The results show, first, that research and development have been the most important determinants of competitive performance and profitability among the largest US drug companies (*ibid.*, p. 142); and secondly, that the strategies to develop external linkages are complementary to the in-house research capabilities of large firms, suggesting that firms with greater 'knowledge capital' can extract greater benefits from such linkages (*ibid.*, pp. 157-8).

The emergence of biotechnology has brought radical change to the industry. Mastery of synthetic organic chemistry is no longer sufficient to ensure continued technological leadership. The linkages are no longer with departments of chemistry and pharmacology, but with molecular genetics and bio-physics, micro-biology, protein chemistry and chemical engineering, to name but a few. Unlike chemistry, biology had no tradition of industrial linkages. It has therefore involved both sides in a learning process. The large chemical or pharmaceutical firms were understandably cautious in their approach and only in the last few years have they begun to invest seriously in building up in-house teams in biotechnology (Grabowski and Vernon, 1994; Sharp, 1995). In the meantime, they have relied extensively on external linkages, either through new biotechnology firms or through direct links with the basic research in universities.

A picture of the complex web of linkages developed in the UK emerges from the study by Senker and Sharp of the SERC's Biotechnology Directorate which was established in 1981 (Senker and Sharp, 1988). The UK pharmaceutical companies - Glaxo, Wellcome, (SmithKline) Beecham and ICI (now Zeneca) - all played a prominent part on the management committee, giving them direct influence in shaping the Directorate's programme and, just as importantly, oversight of all grant applications. Interestingly, these same companies chose not to follow the lead of most of their competitors in other countries and link up with new biotechnology firms in the United States. Rather, all have continued to make extensive use of the UK science base, claiming that the overall quality of the research in the UK is in general equivalent to that in the US and very much cheaper (Senker, Joly and Reinhart, 1996). CASE studentships, LINK schemes and other initiatives have encouraged such behaviour - indeed Britain probably has a wider array of schemes encouraging such linkages than any other European country. It is noteworthy that this trend is mirrored by the large number of collaborative publications. In their work examining publication by the world's large companies, Hicks *et al.* (1996) found that, amongst European chemical and pharmaceutical firms, ICI published more than any of its European counterparts, and published more in collaboration with university researchers - and especially British university researchers - than the other companies. In other words, as suggested by the evaluation/case study material, it appears that UK chemical and pharmaceutical companies are deeply embedded in the basic research carried out in British academic institutions.

There is circumstantial evidence to link this close relationship to the success of the pharmaceutical industry in Britain, a success that is perhaps best illustrated by two sets of statistics. First, in terms of 'league tables', the only British company to reach the top 20 pharmaceutical companies world-wide in 1976 was Glaxo at 20th position. By 1994, Glaxo topped the league table, two other British companies (SmithKline Beecham and Wellcome) came within the top 20 and Zeneca, the pharmaceutical/agricultural product half of the old ICI, came 23rd. Secondly, between them, these four companies sold 14 out of the 50 top selling drugs compared to 26 from US companies, 3 from German, 3 from Swiss, 3 from Japanese and 1 from a Swedish company (Sharp and Patel, 1996). Indeed, one of the most striking features of the last 20 years in the pharmaceutical industry had been the emergence of this strong cohort of British firms, while at the same time Britain has attracted a large number of foreign multinational laboratories.

On the basis of a comparison of the relative success of the British and French industries over the years 1960-90, Thomas (1994) has suggested that the British price control structures which favoured innovative over ‘me-too’ drugs played some part in orienting the British firms towards innovative drug discovery. Brech and Sharp, in an earlier study on inward investment in pharmaceuticals found that the strength of academic chemistry, pharmacology and molecular biology has been a factor attracting multinational R&D laboratories, but that favourable treatment under the price regulation system has also been an important initial attractor (Brech and Sharp, 1985, pp. 48-49). They concluded that the presence of a large number of multinationals in Britain contributed to the competitiveness of the industry, echoing an earlier econometric study by Lake who found that “the transfer of technology at market level has stimulated UK companies both to conduct research of a high quality and to perform competitively within a wide range of drug technologies” (Lake, 1976). Brech and Sharp suggest that the large number of multinational pharmaceutical subsidiaries in Britain who have employed British nationals in substantive managerial roles, both in R&D and in marketing, have trained a management cadre which has ‘thought globally’ and has provided the capabilities underpinning the British success (Brech and Sharp, 1985, p. 55).

6.4 UK basic research and the location of corporate R&D

In this section, we discuss the reasons why foreign companies locate R&D in the UK, and why UK (or European) companies conduct R&D in the US. Before doing this, though, we should note that there is an ongoing debate about the significance of multinational companies’ overseas R&D. The early literature stressed the role of home markets in determining firms’ technological advantages. Successful export activities led on to the establishment of overseas production facilities and any associated R&D activity was mainly concerned with adapting products to meet local tastes (Vernon, 1966). An analysis of the US patenting activity of the world’s largest 539 firms indicates that, for the majority, technology production remains close to the home base (Patel, 1995). Moreover, when these firms locate R&D activities abroad, no systematic relationship is found between their presence in a technical field and the relative technological strength of the host country in that area (Patel, 1996); there is no evidence of any relationship with the scientific strength of the host country in specific fields. The globalisation of the technological activities of large multinational firms is now accelerating. Some suggest this may reflect a desire to have a ‘window on foreign science’ and be related to the strength of the science and technology base and the availability of qualified scientists and engineers, with no special bias towards the home country (e.g. OECD, 1992).

In comparison with other large European countries, British industrial R&D is much more internationalised. In the late 1980s, about 45 per cent of the R&D by large British firms was performed outside the UK, compared to between 10 and 20 per cent by equivalent French, German and Italian firms. The main foreign location for British firms’ R&D was the US. The share of R&D performed overseas was relatively high in traditional sectors (paper and board, building materials, food, drink and tobacco), as well as in chemicals, petroleum refining and non-electrical machinery. In pharmaceuticals, the share was about 25 per cent (SPRU Large Firm Data Base). Possible reasons for this emphasis on overseas R&D include the desire to obtain a higher share of foreign production, corporate strategies such as foreign take-overs (particularly in English-speaking countries), greater proximity to local markets and sources of raw materials, and dissatisfaction with or lack of integration into the UK science base.

Offsetting the large 'export' of R&D by British-based companies is the fact that a relatively large share of industrial R&D in Britain is performed by foreign-owned firms - approximately 20 per cent, which is again about twice that in France, Germany and Italy. The foreign shares in the UK are relatively high (about 30 per cent) in both fine chemicals (a field of UK technological strength) and electronics (a field of relative weakness). In the former, as noted above, various factors seem to have attracted foreign firms to perform R&D in the UK. In the latter, the progressive withdrawal over the past 25 years of major British-owned firms from computing, semiconductors and consumer electronics has automatically increased the foreign share of the total (Patel and Pavitt, 1987). For example, approximately 80 per cent of the scientific papers published by companies in the engineering and instrument sector are produced by foreign firms, compared with only 25 per cent in the case of papers produced by firms in the chemical sector (SPRU BESST database). A major question for the future, therefore, is the degree to which industrial R&D in British electronics is dynamic enough to exploit efficiently the British basic research that is potentially useful for electronics-related technologies. If not, what could be done to encourage foreign firms to expand their UK-based activities?

6.4.1 Foreign Multinationals' R&D Investment in the UK

What are the reasons why foreign firms carry out R&D in the UK? And how does this vary across sectors? Stoneman has shown that overseas financing of industrial R&D in the UK is larger than in other comparable economies and is growing. Funding is concentrated in four main industrial sectors: aerospace, chemicals, electronic equipment and components, and office machinery and computers. He suggests that the three main factors attracting R&D facilities to the UK are the supply of highly skilled manpower, a strong university system and the relatively low costs of UK qualified scientists and engineers (Stoneman, 1989).[24] Similarly, Taggart (1989) has surveyed US and European pharmaceutical companies on the reasons why they have set up R&D laboratories in the UK. Three of the five main determinants he identified were a "high present stock of scientists, engineers and technologists", a "high level of competitors' R&D activity", and "excellence of tertiary education system" (the other two were "strategic importance of firm's presence in the market" and "efficient patent laws"). Webster (1994) has also investigated the issue, focusing on long-term, large-scale collaborations between a single company and an academic research group in biotechnology and the biosciences. He found that foreign companies enter into these strategic research alliances with the more prestigious university centres (especially Oxford and Cambridge), suggesting that the quality of the academic base may be an important factor.

The Japanese External Trade Organisation (JETRO) carries out an annual survey of the operations of Japanese companies in the manufacturing sector. The 1994 survey found that, of the 206 Japanese manufacturers operating in the UK, 83 had British R&D bases, of which 19 were independent of any manufacturing facilities. The main reason why companies locate R&D facilities in the UK is to meet local needs (86 per cent of respondents). Subsidiary reasons are "to expand the range of research and development through foreign researchers' ideas and way of thinking" (27 per cent) and "shortage of personnel engaged in research and development in Japan" (17 per cent - see Table V-3 in JETRO, 1994, p. 53). The former reason was particularly important for companies which had set up independent R&D centres.

---

[24] However, some of the data upon which his analysis is based may be misleading; for instance, what appears to be overseas funding may be an artefact of the location of a group's corporate office.

There is a limited amount of anecdotal evidence to expand on the reasons for some Japanese companies' R&D activities in the UK. In 1990, Toshiba set up its Cambridge Research Centre to develop the next generation of microchip technology. It chose Cambridge because of the leading-edge, high-quality basic research at the Cavendish Laboratory on exploiting quantum mechanics in microchip research, and it appointed the head of the research group, Professor Pepper, to direct its new laboratory (*Guardian*, 12 December 1990). Eisai invested £50M in building and running a research laboratory at University College, London to develop treatments for Alzheimer's disease. University College was chosen because of its excellence in neuroscience (*Guardian*, 12 September 1990). Canon established its European Research Centre at Surrey University Science Park to exploit British research strength in loudspeaker technology. Similarly, Kobe Steel decided to set up British research facilities to exploit local strength in chemistry. The laboratory carries out work on polymers, composites and diamond thin films, and it funds relevant basic research in British universities. In all these examples, it would seem that foreign companies have identified areas of scientific strength and leading researchers in the UK with whom they wish to develop closer links. This evidently cannot be done at a distance simply by reading the scientific papers produced by those researchers.

6.4.2 European Multinationals' R&D Investments in the US

Within the last two decades, Europe's chemical and pharmaceutical firms have recognised that continued success demands that they build up in-house expertise in biotechnology. Accordingly, they have made considerable efforts to acquire the necessary capabilities. However, the leading edge of research in biotechnology has remained in the US where the emergence of a dynamic new sector based on small specialist research firms closely linked to academia has led to an 'explosion' of related science and technology. As a result, many of the leading multi-national firms, including French and German-based companies as well as British ones, have found it necessary to develop a means to access American knowledge and capabilities. To this end, they have set up new US laboratories (or extended existing ones), and negotiated contracts with US academic laboratories or dedicated biotechnology companies. These same companies have at the same time retained their established links with their indigenous science bases and forged new linkages in the area of the life sciences (Sharp *et al.*, 1993).

A recent follow-up study investigated the factors which influenced ten leading European multinationals to locate biotechnology research in the US, and the effect of overseas research on European biotechnology capabilities. The findings indicate that the multinationals employ roughly twice as many biotechnology researchers in Europe as in their US subsidiaries, but that US laboratories often recruit European-born researchers from among post-doctoral fellows at leading US universities. Multinationals are moving some areas of research to the US because of gaps in European expertise - namely in microbial and mammalian cell technology, bio-informatics and combinatorial chemistry. Companies expressed concern about the lack of breadth in European research, with over-concentration on cell biology, molecular biology and immunology. The study indicates large gaps in European research and training, with a loss of talent from Europe to the US at the post-doctoral level. It is not clear whether scientists are attracted to work in the US by the science, or whether limited opportunities, poor salaries and inadequate conditions for post-doctoral work in Europe drive them abroad. For instance, the researchers were told that academic biotechnology research in Europe is adversely affected by under-capitalisation. This view is supported by company perceptions that European public sector research is less well equipped than US. Post-doctoral training abroad is advantageous, but there may be cause for concern if a large proportion of European post-doctoral fellows are subsequently recruited to work in the US (Senker, Joly and Reinhard, 1996).

The major reasons for the location of laboratories in the US are the size of the market, the need to comply with FDA regulations and the desire to tap into US science. In addition, companies have found that the general environment for commercialising biotechnology is more conducive in the US than Europe, especially in terms of regulation and patenting, but also as regards the general public acceptance for biotechnology. The results of this study indicate that the US activities of European chemical and pharmaceutical multinationals are helping to increase their biotechnology capabilities in Europe in certain areas where Europe has weaknesses, for instance in gene therapy, genomics and combinatorial chemistry. The European-based laboratories are involved in large strategic alliances with US dedicated biotechnology firms in these areas, with knowledge flowing directly from the US to Europe. However, in areas where European public sector research is especially weak, such as microbial physiology and virology, companies are shifting related research activities to the US, so exacerbating those existing weaknesses (*ibid.*).

We have seen in Section 6 that the basic research carried out in universities and other public sector laboratories is of central importance to industry, with UK strength in certain research areas being a crucial factor in attracting foreign companies to fund and carry out research and development in Britain on a large and growing scale. At the same time, European companies (including British ones) are increasingly investing in research in other countries, especially in the United States and in the biotechnology sector. This is consistent with the conclusion of Hirst and Thompson (1996) that multinational corporations are nowadays locating their activities in areas rich in skills rather than those rich in cheap labour.

7.0 FOREIGN EXPERIENCES

7.1 Determining the level of expenditure on basic research

The issue that we were asked to address here concerns the criteria used by governments in other leading industrial countries to determine the level of public funding for basic research. In this section, we briefly review the factors influencing the level of government expenditure on basic research in a number of countries.

In the United States, some 15 federal agencies provide support for basic research, while substantial sums are also received by public universities from state governments. There is, however, no single federal budget for basic research, merely the aggregate effects of individual expenditure decisions by different government departments and agencies (the principal ones being the National Science Foundation and the National Institutes of Health). The process for setting basic research budgets is complex, and the eventual outcome is more the product of an adversarial political process - involving federal agencies, the Executive Office, Congress and the research community - than the consequence of using explicit criteria (Teich, 1986; Irvine, Martin and Isard, 1990. p. 135).

During the 1980s, US Government spending on basic research increased appreciably, with an annual growth rate of nearly 5 per cent in real terms (Teich and Gramp, 1988, p. 7). Over this period, basic research went from being the smallest component of civil R&D (constituting 28 per cent of the total in 1980) to the largest (with 43% by 1986). Underlying this fundamental shift in emphasis was “the premise that sustained investment in basic scientific research will contribute to long-term economic growth, improve the quality of life, and bolster national defence” (*ibid.*, p. 31). Despite the Administration’s reservations about ‘interfering’ in applied R&D, it was felt that the Federal Government did have a legitimate role to play in stimulating long-term technical change through the direct support of basic research (Irvine, Martin and Isard, 1990. p. 139).

Federal funding of university research likewise grew rapidly during this period (by 4 per cent per annum in real terms). One factor here was the influential Packard-Bromley report which called for a doubling of support over the next decade. The authors argued that university-based research and education were fundamental to the national scientific enterprise, a view that was largely accepted by the Administration (*ibid.*, p.140). After a lean period in the early 1980s, the National Science Foundation also had a resurgence in its fortunes. Under the directorship of Erich Bloch, it successfully linked the justification for its budget to economic competitiveness. Bloch argued forcibly that the United States needed to invest much more in the basic science and engineering fields underlying new technologies. With its increased funds, the Foundation gave particular emphasis to fields likely to underpin emerging technologies, with engineering, mathematics, computer science and materials research being the principle beneficiaries. Support from National Institutes of Health for basic research in the biomedical area also grew rapidly, reflecting the high political priority accorded to health in the United States (*ibid.*, pp. 140-141).

In Germany, the promotion of research is a joint responsibility of the *Bund* (Federal Government) and the *Lander* (states). In the case of the former, a large part of the funding for basic research comes from the Federal Ministry of Education and Research, BMBF (formed from the merger of the Ministries for Education and Science, BMBW, and for Research and Technology, BMFT). This supports basic research through the Deutsche Forschungs-gemeinschaft (DFG) and the Max-Planck Society (MPG), through core funding of universities and various research centres, and through its own research programmes. In all but the last of these, the state governments also contribute (*ibid.*, pp. 50-52). Over recent years, there has been some discussion in BMFT and BMBF over levels of spending on basic research compared with applied research. As in the United States, however, it is not so much a question of explicit criteria being used to determine this, but rather a political ‘gut feeling’ that basic research funding should be a little higher or lower than last year. In addition, state governments have been playing a growing role; for example, some have provided extra resources to increase the research capacity of their universities and institutes (and the output of trained researchers) in targeted areas such as computer science, materials research, engineering and environmental sciences.

It should be stressed, however, that the federal system of government operating in Germany and the United States means that one cannot easily draw lessons for other countries for at least two reasons. First, in a federal system, it is difficult for one part of government to ‘lay down the law’ because other parts have rights and sovereignty. Secondly, such a system inevitably creates a degree of political competition between layers of government, which makes it difficult for administrations to set an overall level of public expenditure.

Compared with other countries, France has a relatively centralised system for government support of research. Like Germany, it has recently merged the Ministries for Education and for Research into a new ‘super-ministry’. This funds basic research through core funding of universities and *grandes écoles* and through various research agencies (or *organismes*), of which the main one is the National Centre for Scientific Research (CNRS). Although there is an overall civil research and development budget, how much of this ends up being spent on basic research depends on individual decisions in the Ministry, CNRS and other *organismes*. There is no evidence that explicit criteria play much part in those decisions. During the 1980s, research was a relatively high priority, especially under the Socialist administrations, and funding for basic research grew rapidly (*ibid.*, Chapter 4). However, since then, the financial constraints have become much tighter.

Basic research in the Netherlands is funded through three main channels. The ‘first flow’ consists of core funding for universities from the Ministry of Education and Science.[25] The ‘second flow’ takes the form of project and programme grants from

---

[25] One university is funded by the Ministry of Agriculture and Fisheries.

research councils and foundations, while contracts awarded to universities by government departments and agencies make up the ‘third flow’. One feature of Dutch policy over the latter part of the 1980s was the move gradually to transfer responsibility for basic research from government departments to the universities and to institutes operated by the Netherlands Organisation for Scientific Research (NWO). This represented one element in a strategy to reshape the national research system which was widely seen as lacking the degree of integration and coherence needed if the country was to maintain an internationally competitive effort in key areas over coming years. After several years in which spending on basic research fell in relative terms as greater priority was given to work on industrial production and technology, the Government decided in 1988 to place science at the top of the Dutch political agenda for the 1990s. In particular, investment in universities has been accorded high priority in view of the longer-term socio-economic significance of many areas of basic research (*ibid.,* pp. 109-110).

In Japan, most of the publicly funded basic research is carried out either in universities (financed largely by the Ministry of Education, Science and Culture) or in government institutes funded by other ministries. During the 1960s and 1970s, government support for applied research grew rapidly (although from a low base - three quarters of R&D is still funded by industry compared with around a half in most other OECD countries). Japanese university research played a relatively minor role, although it was certainly helpful in interpreting the significance of foreign research for Japan. However, in 1986, the Cabinet accepted new national policy guidelines for research. These stressed Japan’s transition from a ‘technological follower’ to a ‘technological leader’, a transition which required, among other things, a shift in emphasis from applied to basic research. The need to increase government funding for basic research was further accentuated around this time by criticisms from abroad, especially the United States, that Japan was ‘free-riding’ on Western efforts in basic research (*ibid.,* pp. 167-174). Particularly worrying were certain attempts by the US to prevent the outflow of scientific information and to discourage inward investment by Japanese enterprises. Greater priority was therefore given to government funding of basic research.

Among the policy initiatives taken since then have been: the introduction of targeted funding for basic research in universities responding to emerging scientific opportunities and socio-economic demands; concentration of investments in major scientific facilities in central research institutes; the promotion of collaborative research between universities and industry; and the development of improved links between Japanese researchers and the international research community (*ibid.*). However, despite the substantial increases in government funding, the country still faces several major problems in relation to basic research. In international terms, Japanese universities are generally rather poorly equipped to carry out frontier basic research. In addition, there is continuing concern that the Japanese educational system and the university structure (especially the continued emphasis on core funding compared with individual project grants) does not encourage the nurturing of creative basic researchers prepared to take risks. Lastly, in the view of some, Japanese basic research is still too disconnected from industry to support it effectively now that Japan has reached the scientific-industrial frontier (e.g. Rosenberg, 1994). In order to contribute new scientific knowledge as well as to absorb it from elsewhere, more basic research is needed in Japan. Without this, it is unlikely to be able to take advantage of opportunities for further development in certain industrial technologies (such as packaged software).

Lastly, mention should be made of the Asian ‘tigers’. South Korea in particular now recognises the strategic importance of basic research. Although it is not yet at a stage of development where it may benefit directly in the short term, it is investing heavily in publicly funded basic research. Besides other ‘tigers’ like Singapore, some of the fast-growing economies in East Asia such as Malaysia are also following this trend.

To sum up: in this section, we have seen how there is no evidence that other countries use systematic criteria in determining the level of funding for basic research. Certainly, there has been no attempt to link that level to the magnitude of the economic benefits that basic research generates. However, in most of the major industrialised countries, there is an emphasis on strengthening basic research in order to enhance technological innovation, industrial competitiveness, and economic and social development.

7.2 Expectations regarding basic research and ensuring value for money

What benefits do foreign governments expect to see from basic research? Expectations vary considerably across countries and over time (for example, as a result of a change in government or shift in ideology). From 1945 to the 1980s (in most industrialised countries), governments had a fairly relaxed attitude towards the expected benefits from science. During this time, the model of basic research put forward in 1945 by Vannevar Bush, the US Presidential science adviser, was widely accepted. According to this, governments put money into basic research and out will come, at some time or other, contributions to wealth, health and national security. There was not too much concern about exactly what form those benefits might take or when they might occur. The model worked well over that period as public funding of basic research grew appreciably in real terms each year in most of the advanced industrial countries.

However, the Bush model began to break down as public expenditure came under strain and demands for greater public accountability grew. The United Kingdom was one of the first to experience such pressures in second half of 1970s. The Netherlands was another early case, although the reasons were slightly different (it was felt that there should be more emphasis on science producing social benefits). The model endured longest in Germany and the United States, only breaking down around 1990. In the German case, this was because of the unexpectedly high costs of unification. In the US, there was the problem of the growing Federal Government deficit together with concern that the model was not working - that Japan rather than the US seemed to be reaping more of the economic benefits from basic research and technological innovation.

Now, in virtually all OECD countries, a new ‘social contract’ for science seems to be emerging. Under this, government will invest in basic research but only if it generates rather more direct and specific benefits in the form of wealth creation and improvements to the quality of life.

This new social contract is seen in perhaps its most extreme form in New Zealand where there have been major organisational changes to the structure of research since the late 1980s. Very influential here has been the notion of ‘contestable markets’ developed by the American economist, William Baumol, and his colleagues (Baumol *et al*., 1982).[26] A key element of reform has been the organisational separation of *policy*, *purchasing* and the *provision* of research. The Ministry responsible for policy advice (the Ministry of Research, Science and Technology, MORST) is seen as competing in a prospective market place, in this case for ministry services to the government (MORST, 1996, pp. 18-19). The Ministry is not responsible for funding or ‘purchasing’ research, that being the responsibility of a notionally separate Public Good Science Fund. Public-sector research outside of the universities is structured mainly into ‘Crown Research

---

[26] The theory of ‘contestable markets’ was originally developed to resolve the economic logic of large utilities in the US. According to the theory, even where ‘natural monopolies’ exist, competitive rather than exploitative behaviour can emerge if the position of the monopolist is understood to be contestable. It is not always necessary to have several competing suppliers in a particular market: the mere *threat* of entry (and replacement) by a possible alternative supplier can be sufficient. In a small country like New Zealand, such situations where there is just a single ‘supplier’ often arise; even organisations that are sole suppliers to the country (i.e. national monopolists) are often uneconomically small, and this problem would be exacerbated if several suppliers actually entered the ‘industry’.

Institutes' (CRIs), which are answerable to the Treasury as well as to the Fund. These, too, are required to perform as if competing in markets (they are formally constituted as companies), undertaking research and related services for the benefit of New Zealand. Although they must operate in a business-like manner (as bound by the Companies Act), their main responsibility is to return a social rather than an economic benefit to New Zealand: "In effect the Government expects a science dividend from the CRIs rather than a financial dividend" (MORST, 1994, p. 4).

Thus, contestability is a key aspect of the New Zealand research funding system. No organisation has a guaranteed or assumed share of any pool of funding. Contestability essentially operates as a vehicle for providers to offer purchasing alternatives and purchasers select from these offers. In principle, it should not create arbitrary (or short-term) market criteria for performance, and to that extent it does not remove responsibility for setting priorities or for evaluation from the government. There are also some who fear that it creates too much uncertainty for an activity like research, and might encourage opportunistic behaviour that in the long term may have adverse consequences.

One indication of the changing social contract between science and society is the rapid spread of technology foresight activities over recent years. Under the Bush model of basic research, it was assumed that giving researchers autonomy to determine the distribution of resources through the peer review system was the best way to co-ordinate scientific progress. However, if science is to be more closely linked to meeting economic and social needs, a new approach is needed that brings together the 'science push' with the 'demand pull' - in other words, that enables the 'users' of the results of research to have an input to decision-making on basic research as well as the researchers themselves. Technology foresight is the process that brings together industry and other 'users' of research results, the scientific community and government to consider longer-term economic and social needs and scientific and technological opportunities (Martin and Irvine, 1984; Martin and Irvine, 1989; Martin, 1993).

Technology foresight has been carried out extensively in Japan since 1970. Besides the well-known 30-year forecasts of the Science and Technology Agency, there are foresight activities at three other levels: (i) individual ministries such as MITI; (ii) industrial associations and other informal groupings of companies; and (iii) individual companies and research institutes. Each level of foresight draws upon and contributes to the other levels. The main benefits arise from the foresight *process*. That process brings together research users, performers and funders and stimulates communication, concentration on the longer-term, co-ordination of research activities, the creation of consensus, and the generation of a commitment to convert the technological opportunities into economic and social benefits.

During the 1980s, technology foresight began to spread to other countries such as France and Sweden, followed by the Netherlands and Australia. Initially, Germany, the United States and Britain remained sceptical about the utility of foresight, but during the first half of the 1990s these countries, too, began to undertake foresight exercises. Inevitably, the first attempts at foresight in each country have not always been fully successful as the foresight process needs to be carefully tailored to local circumstances. However, gradually technology foresight has begun to take root and is coming to be seen as one of the tools for ensuring that research, in return for public funding, meets the expectations of the public and their elected representatives.

The final question to be considered is how governments assess the value for money from their investment in basic research. In 1986, the US Office of Technology Assessment carried out a detailed study and produced a report entitled *Research Funding as an Investment: Can We Measure the Returns?* In broad terms, the conclusion was that the various possible approaches were all too simplistic and potentially misleading. This is consistent with the findings of more recent reviews (e.g. Congressional Budget Office, 1993; Popper, 1995) and with the review of the literature carried out in this study. Nevertheless, as part of the new social contract for science, in most industrialised countries there are demands for greater public accountability, with more emphasis on the evaluation of research funded by government. In the United States, for example, Congress passed the Results and Performance Act in 1993 which requires federal agencies to establish procedures for monitoring and evaluating the output of all federally funded programmes. Until now, 'value for money' has been less of an issue in continental Europe than in the UK and the US. However, as the constraints on public expenditure grow (not least to meet the Maastricht targets), that situation is likely to change. The task over coming years will be to produce better methodological tools to meet that challenge.

In summary: the expectations that the state and society have in relation to basic research are changing. We are witnessing the emergence of a new 'social contract' for basic research under which the public and government expect more direct and specific benefits from their investments in this research. Technology foresight offers one means to link research to longer-term economic and social benefits. However, there are currently no methods for estimating the value for money from publicly funded basic research in a reliable manner.

8.0 CONCLUSIONS

In this brief study, we have carried out a review of the literature on the relationship between publicly funded basic research and economic performance. As we have seen, there is an extensive literature that touches upon this topic. In Section 8.1, we summarise the broad findings from our review, while in Section 8.2 we relate these specifically to the six issues that we were asked to address by the Treasury.

8.1 Main findings

8.1.1 Econometric studies

The principal conclusions to emerge here are the following:

- There have been numerous attempts to estimate the impact of research 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 basic 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.

- The econometric literature on localisation effects and spillovers suggest that advanced industrial countries need their own, well developed basic research capabilities in order to sustain technological development. Personal links and mobility are vital in integrating basic research with technological development. This, in turn, points to the importance of linking basic research to post-graduate training, ensuring that the latter is carried out in organisations at the forefront of their research field, a point also emerging from Section 5.

- One can attempt to estimate the rate of return to basic research but only on the basis of very questionable assumptions. Mansfield's work suggests that there is a very substantial rate of return, but the precise figure he arrives at (28 per cent) is open to some doubt.

- Among the problems with estimating the rate of return 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 technologies.

- Because of the highly complex ways in which the benefits of basic research are captured, and because the routes by which this happens often do not lend themselves to economic quantification, it is neither logical nor feasible to use estimates of the rate of return to publicly funded basic research in order to decide what should be the level of public funding for basic research.

8.1.2 Surveys and case studies of different forms of economic benefit from basic research

Among the main findings here are:

- The traditional justification for the public funding of basic research 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 surveys and case 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.

- New instrumentation and methodologies are important, both within science, and as a form of output or economic benefit from basic research. 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.

- The skills developed by those involved in carrying out basic research, especially graduate students, also lead to substantial economic benefits as individuals move on from basic research, carrying with them both codified and tacit knowledge. When faced with a particular problem, someone trained in basic research may not have the solution readily to hand, but they may know where to find the information or skills required to solve it.

- The tacit knowledge and skills generated by basic research are especially important in newly emerging and fast-moving areas of science and technology.

- Participation in basic research is essential if one is to obtain access to national and international networks of experts and information.

- 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.

- Basic research may also 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 on 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 - in other words, 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 larger benefits of trained researchers, improved instrumentation and methods, tacit knowledge, and membership of national and international networks. It should not, therefore, be used as the basis for policy measures.

- The overall conclusion 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 system to make the most effective use of them.

8.1.3 Basic research in the United Kingdom

The conclusions here can be summarised as follows:

- The literature on the relationship between companies and publicly funded basic research shows that the use made of such research by companies varies widely across sectors. Basic research contributes both through trained scientists and as source of new useful knowledge. Much of the contribution of publicly funded basic research to industry comes in the form of small and often largely invisible flows. Companies generally need a strong internal research capability in order to use and exploit external knowledge effectively.

- There is some literature on basic research and national competitiveness. At the macro-level, the relationship between basic research and UK industrial performance is unclear. At the sector level, in the case of chemicals and pharmaceuticals, there is both a strong science base and internationally competitive industrial performance, with many of the links between basic research and industry being relatively direct. In electronics, in contrast, industrial performance has been weaker and the science base is also less strong.

- However, attempting to identify single causes to explain the competitiveness of specific sectors of industry is fraught with danger. A more appropriate approach may be to assess the strength of both the relevant science base and an industrial sector's propensity to invest in corporate R&D. Also of importance here is the nature of the links between basic research and commercial exploitation - whether they are simple and direct, or whether they are more indirect and longer-term, taking the form of a multi-link chain.

- Data on the location of corporate R&D shows that UK industrial R&D is comparatively internationalised. Approximately 45% of UK company R&D is performed overseas, and about 20% of company R&D in UK is carried out by foreign companies. This high level of internationalisation brings substantial spin-off benefits to the UK in terms of being integrated more fully into international research networks.

- Investment by UK companies overseas, in particular in US biotechnology, is driven by the need to access US knowledge and capabilities together with other factors such as the large North American market, access to raw materials and the US regulatory regime. In some cases, dissatisfaction with the UK science base may also be a factor. Such overseas links may help to strengthen a company's research capabilities, but they may also exacerbate existing weaknesses in UK basic research.

- The high level of investment by overseas companies in UK R&D is driven by the desire to access advanced skills, the existence of strong basic research teams in universities, and the relatively low costs of British researchers.

8.1.4 *Foreign Experiences*

Here, there are two principal findings:

- There is no evidence that other countries use systematic criteria in determining the level of funding for basic research. Certainly, there has been no attempt to link that level to the magnitude of the economic benefits that basic research generates. However, in most of the major industrialised countries (and more recently in the fast-growing economies of East Asia), there is an emphasis on strengthening basic research in order to enhance technological innovation, industrial competitiveness, and economic and social development.
- The expectations that the state and society have in relation to basic research are changing. We are witnessing the emergence of a new 'social contract' for basic research under which the public and government expect more direct and specific benefits from their investments in this research. Technology foresight offers one means to link research to longer-term economic and social benefits. However, there are currently no methods for estimating the value for money from publicly funded basic research in a reliable manner.

8.1.5 *The rationale for public funding of basic research*

Numerous studies over the last 25 years have indicated that market forces lead to sub-optimal investments in basic research. Nevertheless, as we have seen in this review, 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 'public good' and 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:[27]

- the argument of Klevorick *et al.* (based on the results of the Yale survey of industrial R&D managers) that basic research represents a source of technological opportunities;
- the view of Callon that basic research provides a source of new interactions, networks and technological options, thus increasing technological diversity;
- the work of 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.

8.1.6 *Policy implications*

This review of the literature has demonstrated that, although its economic benefits are hard to quantify, basic research is absolutely crucial for the UK's strategic position 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.

---

[27] Another possible contribution (although it has not been discussed here) is the work of Gibbons *et al.* (1994) on the new production of knowledge - in particular, the concept of 'Mode 2' production.

However, for a number of reasons emerging from this review, it is difficult to arrive at simple policy prescriptions. Those reasons include:

- variations in the forms of interaction between basic research, technology and innovation, and in the relative importance of the different forms of economic benefit, with scientific field, technology and industrial sector;
- 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;
- the importance of 'spillovers', including both localisation effects and the interactions between one activity and another.

In short, there can be no simple unified policy for basic research. Nevertheless, a number of lessons emerge from this review:

- Policies must ensure that basic research continues to be closely integrated with the training of postgraduate students.
- Given the significant contribution to innovation which can flow from new instrumentation, research grants should include adequate resources for acquiring or accessing the latest instrumentation, for developing experimental facilities and new methodologies, and for funding technicians to assist in these tasks.
- The evidence that skilled graduates who enter industry are one of the major channels 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 in the case of firms that currently lack this resource.
- Since a single piece of basic research may contribute to a large number of different technological and product developments, we continue to need a portfolio-based approach to the public funding of basic research, along with a continuing emphasis on responsive mode funding.
- 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.

8.2 Conclusions on the six issues

In this study, besides reviewing the literature on the economic effects of basic research more generally, we were also asked to consider the six issues set out in Section 1. Our conclusions in relation to these can be summarised as follows:

- Publicly funded basic research seems to have a substantial impact on productivity. Most of the productivity increases this century have come from our mastery over technology, and a large part of this has derived from a better understanding of the basic scientific processes underlying technology.
- This trend seems likely to continue since new technologies appear to be increasingly dependent on advances in basic research. Without the basic research, we cannot explore the underlying scientific processes and this will greatly hinder our ability to produce further technological advances in the future.

- However, the methodologies to quantify the impact of publicly funded basic research on productivity are seriously flawed. In particular, they tend to ignore the non-information forms of output or benefit.

- The relationship between basic research and performance in specific industries depends as much on the attitude and approach of companies as on the strength of the basic research. In the UK, that attitude seems to be more positive and far-sighted in companies drawing upon the results of basic research in chemistry and biology than those drawing upon physics and much of engineering research. However, just as important may be the fact that the latter companies are faced with the multi-link chains between basic research and commercial exploitation that are more difficult to nurture and manage.

- In the specific case of the chemical and pharmaceutical industry, there is a good deal of evidence to suggest that the UK's strength in these sectors is linked to the strength of basic research in universities. The link, however, is two-way. The traditional linkages between the chemical industry and university chemistry laboratories stimulated that area of research. This is less true in the case of molecular biology which was supported for many years by MRC before potential pay-off began to emerge.

- Until recently, most multinational companies conducted the great majority of their research in their home country. However, evidence is emerging that some are now locating research activities in areas which have a strong science base and in particular are rich in scientific skills.

- There is only a small amount of evidence on how aware British companies are of publicly funded basic research, or on whether they are better or worse informed than foreign competitors. Although many are aware of government-funded collaborative research programmes, with a few prominent exceptions they do not appear to adopt as systematic approach to gathering intelligence about scientific research from around the world as some of their competitors in Japan and the United States.

- There is no sign that explicit criteria are used in other countries to determine the level of public funding of basic research. That level depends partly on general perceptions as to how important a role basic research is likely to play in relation to the development and exploitation of new technologies, but just as important are other factors such as the prevailing government philosophy and international comparisons or pressures.

- Government expectations about the benefits from basic research are changing. A new 'social contract' is emerging in which there are more specific expectations that basic research should generate economic and social benefits in return for the substantial public funds that it receives.

APPENDIX 1

A1. Bibliography[a]

Achilladelis, B., A. Schwarzkopf and M. Cines (1987), ‘A Study of Innovation in the Pesticide Industry’, *Research Policy,* 16, pp. 175-212.

Achilladelis, B., A. Schwarzkopf and M. Cines (1990), ‘The Dynamics of Technological Innovation: the Case of the Chemical Industry’, *Research Policy*, 19, pp. 1-34.

Achilladelis, B. (1993), ‘The Dynamics of Technological Innovation: the Sector of Antibacterial Medicines’, *Research Policy,* **22**, pp. 279-308.

Acs, Z. J., D. Audretsch and M. Feldman (1991), ‘Real Effects of Academic Research: Comment’, *American Economic Review*, 82, pp. 363-367.

Adams, J.D. (1990), ‘Fundamental Stocks of Knowledge and Productivity Growth’, *Journal of Political Economy*, 98, pp. 673-702.

Archibugi, D. and M. Pianta (1992), *The Technological Specialisation of Advanced Countries*, Kluwer Academic Publishers, Dordrecht.

Arrow, K. (1962), ‘Economic Welfare and the Allocation of Resources for Invention’, in R. Nelson (ed.), *The Rate and Direction of Inventive Activities*, Princeton University Press, Princeton, pp. 609-625.

Arundel, A., G. van de Paal and L. Soete (1995), *PACE Report: Innovation Strategies of Europe’s Largest Industrial Firms: Results of the PACE Survey for Information Sources, Public Research, Protection of Innovations, and Government Programmes*, Final Report, MERIT, Limburg University, Maastricht.

Autio, E. (1995), *Sympletic and Generative Impacts of New Technology-Based Firms in Innovation Networks: An International Comparative Study,* Doctoral Dissertation, Institute of Industrial Management, Helsinki University of Technology, Helsinki.

Australian Bureau of Industry Economics (1993), *R&D, Innovation and Competitiveness: An Evaluation of the Research and Development Tax Concession,* Research Report No. 50, Australian Government Publishing Service, Canberra.

Australian Industry Commission (1995), *Research and Development,* Volumes 1-3, Report No. 44, Australian Government Publishing Service, Canberra.

Bach, L., P. Cohendet, and M.-J. Ledoux (1995), ‘The Evaluation of Big R&D Projects: A Comparison between the BRITE-EURAM Projects and the ESA Space Projects’, *International Journal of Technology Management*, 10, pp. 525-556.

Balmer, B. and M. Sharp (1993), ‘The Battle for Biotechnology: Scientific and Technological Paradigms and the Management of Biotechnology in Britain in the 1980s’, *Research Policy,* 22, pp. 463-478.

Bania, N., R.W. Eberts and M.S. Fogarty, ‘Universities and the Startup of New Companies: Can We Generalise from Route 128 and Silicon Valley?’, *Review of Economics and Statistics*, 75, pp. 761-66

Baumol, W. J., J. C. Panzar and R. D. Willig (1982), *Contestable Markets and the Theory of Industry Structure*, Harcourt, Brace, New York.

---

[a] The bibliography includes a number of references which are not cited in the text but which are nevertheless useful background reading.

Bell, G. and M. Callon (1995), ‘Techno-Economic Networks and Science and Technology Policy’, *STI Review*, pp. 59-117 (OECD, Paris).

Betz, F. (1994), ‘Basic Research and Technology Transfer’, *International Journal of Technology Management*, 9, pp. 784-796.

Bloch, E. (1988), ‘Basic Research: the Key to Economic Competitiveness’, *International Journal of Technology Management*, 3, pp. 393-404.

Brech, M. and M. Sharp (1983), *Inward Investment: Policy Options for the UK*, Chatham House Papers No 21, Routledge and Kegan Paul for the Royal Institute of International Affairs, London.

Brooks, H. (1994), ‘The Relationship Between Science and Technology’, *Research Policy*, 23, pp. 477-86.

Bureau d’Economie Theoretique et Appliquée (BETA) (1993), *Economic Evaluation of the Effects of the BRITE-EURAM Programmes on the European Industry*, Final Report for DG XII-4 Evaluation Unit, Brussels.

Callon, M. (1994), ‘Is Science a Public Good’, *Science, Technology and Human Values*, 19, pp. 395-424.

Cohen, W. and D. Levinthal (1989), ‘Innovation and Learning: the Two Faces of R&D’, *Economic Journal*, 99, pp. 569-596.

Congressional Budget Office (1993), *A Review of Edwin Mansfield’s Estimate of the Rate of Return from Academic Research and its Relevance to the Federal Budget Process*, CBO Staff Memorandum, April, pp. 1-26.

Dasgupta, P. (1988), ‘The Welfare Economics of Knowledge Production’, *Oxford Economic Review*, 4, pp. 1-12.

Dasgupta, P. and P. David (1994), ‘Towards a New Economics of Science’, *Research Policy*, 23, pp. 487-521.

Dasgupta, P. and J. Stiglitz (1980), ‘Industrial Structure and the Nature of Innovative Activity’, *Economic Journal*, 90, pp. 266-293.

David, P. and D. Foray, (1995), ‘Accessing and Expanding the Science and Technology Base’, *STI Review*, pp. 13-68 (OECD, Paris).

David, P., D. Mowery, and W. E. Steinmueller (1992), ‘Analysing the Economic Payoffs from Basic Research’, *Economics, Innovation, and New Technology*, 2, pp. 73-90.

Denison, E. (1985), *Accounting for Growth*, Harvard University Press, Cambridge, Mass.

Dresch, S. P. and K. R. Janson (1987), ‘Giants, Pygmies, and the Social Costs of Fundamental Research or Price Revisited’, *Technological Forecasting and Social Change*, 32, pp. 323-340.

Ernst & Young (1994), *European Biotech 1994: A New Industry Emerges*, Ernst & Young International Ltd., Brussels.

Fagerberg, J. (1994), ‘Technology and International Differences in Growth Rates’, *Journal of Economic Literature*, 32, pp. 1147-1175.

Faulkner, W. (1995), ‘Conceptualising Knowledge Used in Innovation: A Second Look at the Science-Technology Distinction and Industrial Innovation’, *Science, Technology and Human Values*, 19, pp. 425-458.

Faulkner, W. and J. Senker (1995), ‘Public-Private Sector Research Linkages in Advanced Technologies’, paper presented at Indo-British Seminar on Industry-Institute Interaction, British Council Division, New Delhi, March 6-7.

Faulkner, W. and J. Senker (1995), *Knowledge Frontiers: Public Sector Research and Industrial Innovation in Biotechnology, Engineering Ceramics, and Parallel Computing*, Clarendon Press, Oxford.

Feldman, M. and R. Florida (1994), ‘The Geographic Sources of Innovation: Technological Infrastructure and Product Innovation in the United States’.

Freeman, C. *et al.* (1963), ‘The Plastics Industry: a Comparative Study of Research and Innovation’, *National Institute Economic Review*, 45, pp. 29-57.

Gambardella, A. (1992), ‘Competitive Advantage from In-House Scientific Research: the US Pharmaceutical Industry in the 1980s’, *Research Policy*, 21, pp. 391-407.

Gambardella, A. (1995), *Science and Innovation: The US Pharmaceutical Industry During the 1980s*, Cambridge University Press, Cambridge.

Gibbons, M. and R. Johnston (1974), ‘The Roles of Science in Technological Innovation’, *Research Policy*, 3, pp. 220-242.

Gibbons, M., C. Limoges, H. Nowotony, S. Schwartzman, P. Scott and M. Trow (1994), *The New Production of Knowledge*, Sage, London

Grabowski, H. and J. Vernon (1994), ‘Innovation and Structural Change in Pharmaceuticals and Biotechnology’, *Industrial and Corporate Change*, 3, pp. 435-450.

Granstrand, O., L. Håkanson and S. Sjölander (1993), ‘Internationalisation of R&D - a Survey of Some Recent Research’, *Research Policy*, 22, pp. 413-430.

Granstrand, O., P. Patel and K. Pavitt (1996), ‘Multi-technology Corporations: Why They Do Not (and Should Not) Focus Only on Their Distinctive Core Competencies’, submitted to *California Management Review.*

Griliches, Z. (1979), ‘Issues in Assessing the Contribution of Research and Development to Productivity Growth’, *Bell Journal of Economics*, 10, pp. 92-116.

Griliches, Z. (1980), ‘Returns to Research and Development Expenditures in the Private Sector’, in J. W. Kendrick and B. Vaccara (eds), *New Developments in Productivity Measurements and Analysis*, University of Chicago, Chicago.

Griliches, Z. (ed.) (1984), *R&D, Patents and Productivity*, NBER/University of Chicago, Chicago and London.

Griliches, Z. (1986), ‘Productivity, R&D, and Basic Research at the Firm Level in the 1970s’, *American Economic Review*, 76, pp. 141-154.

Griliches, Z. (1995), ‘R&D and Productivity’ in P. Stoneman (ed.), *Handbook of Industrial Innovation*, Blackwell Press, London.

Hall, B. H. (1993), ‘Industrial Research During the 1980s: Did the Rate of Return Fall?’, *Brookings Papers: Microeconomics*, 2, pp. 289-343.

Hicks, D. (1992), ‘Instrumentation, Interdisciplinary Knowledge and Research Performance in Spin Glass and Superfluid Helium Threes’, *Science, Technology and Human Values*, 17, pp. 180-204

Hicks, D. (1995), 'Published Papers, Tacit Competencies and Corporate Management of the Public/Private Character of Knowledge', *Industrial and Corporate Change*, 4, pp. 401-424.

Hicks, D. M., P. A. Isard and B. R. Martin (1996), 'A Morphology of Japanese and European Corporate Research Networks', *Research Policy*, 25, pp. 359-78.

Hirst, P., and G. Thompson (1996), *Globalization in Question: the International Economy and the Possibilities of Governance*, Polity Press, Cambridge.

Irvine, J. and B. R. Martin (1980), 'The Economic Effects of Big Science: the Casee of Radio Astronomy', *Proceedings of the International Colloquium on Economic Effects of Space and Other Advanced Technologies*, Paris: European Space Agency (ESA SP-151),

Irvine, J. and B. R. Martin (1984), *Foresight in Science: Picking the Winners*, Pinter Publishers, London.

Irvine, J., B. R. Martin and P. Isard (1990), *Investing in the Future: an International Comparison of Government Funding of Academic and Related Research*, Edward Elgar, Aldershot and Brookfield, Vermont.

Jaffe, A. (1986), 'Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value', *American Economic Review*, 76, pp. 984-1001.

Jaffe, A. (1989), 'Real Effects of Academic Research', *American Economic Review*, 79, pp. 957-970.

Japan External Trade Organization (JETRO) (1994), *The 10th Survey of European Operations of Japanese Companies in the Manufacturing Sector*, Europe Division, Overseas Research Department, JETRO, London.

Jevons, W. S. (1866), *The Coal Question: An Inquiry Concerning the Progress of the Nation and the Possible Exhaustion of Our Coal Mines*, Macmillan, London.

Jewkes, J., D. Sawyer and J. Stillerman (1958), *The Sources of Invention*, Macmillan, London.

Johnston, R., C. Cliff and A. Clarkson (1989), *The Return on Investment in R&D*, Centre for Technology and Social Change, University of Wollongong, Wollongong.

Kash, D. E. and R. W. Rycroft (1995), 'U.S. Federal Government R&D and Commercialisation: You Can't Get There From Here', *R&D Management*, 25, pp. 71-89.

Katz, J. S. (1994), 'Geographical Proximity and Scientific Collaboration', *Scientometrics*, 31(1), pp. 31-43.

Kenney, M. (1986), *Biotechnology: The University-Industry Complex*, Yale University Press, New Haven, Conn.

Kenney, M. and R. Florida (1994), 'The Organisation and Geography of Japanese R&D: Results from a Survey of Japanese Electronics and Biotechnology Firms', *Research Policy*, 23, pp. 305-323.

Klein, J. (1994), 'Measuring the Economic Benefit from R&D: Results from the Mass, Length, and Flow Programmes of the UK National Measurement System', *R&D Management*, forthcoming.

Klevorick, A. K., R. Levin, R. Nelson and S. Winter (1995), ‘On the Sources and Significance of Inter-Industry Differences in Technological Opportunities’, *Research Policy*, 24, pp. 185-205.

Lake, A. (1976), Foreign Competition and the UK Pharmaceutical Industry, NBER Working Paper No 155, Cambridge.

Levin, R., A. K. Klevorick, R. R. Nelson, and S.G. Winter (1987), ‘Appropriating the Returns from Industrial R&D’, Brookings Papers on Economic Activity, pp. 783-820.

Lyall, C. (1993), *The 1993 White Paper on Science and Technology: Realising Our Potential or Missed Opportunity?*, MSc dissertation, Science Policy Research Unit, University of Sussex, Brighton.

Mairesse, J. and M. Sassenou (1991), ‘R&D and Productivity: A Survey of Econometric Studies at the Firm Level’, *STI Review*, No. 8 (April) (OECD, Paris).

Malerba, F. (1992), ‘Learning by Firms and Incremental Technical Change, *Economic Journal* 102, pp. 845-859.

Mansfield, E. (1984), ‘R&D and Innovation: Some Empirical Findings’, in Z. Griliches (ed.), *R&D, Patents, and Productivity*, University of Chicago Press, Chicago.

Mansfield, E. (1991), ‘Academic Research and Industrial Innovation’, *Research Policy*, 20, pp. 1-12.

Mansfield, E. (1992), ‘Academic Research and Industrial Innovation: A Further Note’, *Research Policy*, 21, pp. 295-296.

Mansfield, E. (1995), ‘Academic Research Underlying Industrial Innovations: Sources, Characteristics and Financing’, *Review of Economics and Statistics*, 77, pp. 55-62.

Martin, B. R. and J. Irvine (1989), *Research Foresight: Priority-Setting in Science*, Pinter Publishers, London and New York.

Martin, B. R. (1993), *Research Foresight and the Exploitation of the Science Base*, Office of Science and Technology, HMSO, London.

Martin, B. R. (1995), ‘Foresight in Science and Technology’, *Technology Analysis and Strategic Management*, 7, pp. 139-168.

Massey, D., P. Quintas, and D. Wield (1992), *High Tech Fantasies: Science Parks in Society, Science and Space*, Routledge, London.

Metcalfe, J. S. (1994), ‘Evolutionary Economics and Public Policy’, *Economic Journal*, 104, pp. 931-944.

Metcalfe, J. S. (1995), ‘The Economic Foundations of Technology Policy: Equilibrium and Evolutionary Perspectives’, in P. Stoneman (ed.), *Handbook of Industrial Innovation*, Blackwell Press, London.

Mohnen, P. (1990), ‘New Technologies and Inter-industry Spillovers’, *STI Review*, No. 7, pp. 131-147.

MORST (1994), *The Science System in New Zealand*, Ministry of Research, Science and Technology, Wellington.

MORST (1996), *Corporate Profile 1995/96*, Ministry of Research, Science and Technology, Wellington.

Mort, J. (n.d.), ‘Science, Technology and Competitiveness: An Evolutionary Perspective’, Working Paper, Xerox Corporation.

Mowery, David (1995), 'The Practice of Technology Policy', in P. Stoneman (ed.), *Handbook of Industrial Innovation*, Blackwell Press, London.

Narin, Francis and D. Olivastro (1994), 'Status Report: Linkage between Technology and Science', *Research Policy*, 21, pp. 237-250.

National Science Foundation (NSF) (1973), *Interactions of Science and Technology in the Innovation Process*, NSF 667, Washington, D.C.

Nelson, Richard R. (1959), 'The Simple Economics of R&D', *American Economic Review.*

Nelson, Richard R. (1982), 'The Role of Knowledge in R&D Efficiency', *Quarterly Journal of Economics*, 97, pp. 453-470.

Nelson, R. R. (1987), *An Introduction to Evolutionary Theory: Models, Empirics, and Policy*.

Nelson, R. R. (1992), 'What is Public and What is Private About Technology' in N. Rosenberg, R. Landau, and D. Mowery (eds), *Technology and the Wealth of Nations*, Stanford University Press, Stanford.

Nightingale, P. (1996), *Knowledge in the Process of Technological Innovation: A Study of the UK Pharmaceutical, Electronic and Aerospace Industries*, Doctoral Dissertation, Science Policy Research Unit, University of Sussex, Brighton, forthcoming.

R. Oakey, W. Faulkner, S. Cooper and V. Walsh (1990), *New Firms in the Biotechnology Industry: Their Contribution to Innovation and Growth*, Pinter Publishers, London.

OECD (1992), *Technology and the Economy*, Organization for Economic Co-operation and Development, Paris.

Office of Technology Assessment (1986), *Research Funding as an Investment: Can We Measure the Returns?*, A Technical Memorandum, Congress of the United States, Washington, D.C.

P. Patel (1995), 'Localised Production of Technology for Global Markets', *Cambridge Journal of Economics*, 19, pp. 141-153.

P. Patel (1996), 'Are Large Firms Internationalising the Generation of Technology? Some New Evidence', *IEEE Transactions on Engineering Management* (forthcoming).

Patel, P. and K. Pavitt (1987), 'The Elements of British Technological Competitiveness', *National Institute Economic Review*, 122, pp. 72-82.

Patel, P. and K. Pavitt (1995a), 'The Nature and Economic Importance of National Innovation Systems', *STI Review*, pp. 9-32 (OECD, Paris).

Patel, P. and K. Pavitt (1995b), 'Patterns of Technological Activity: Their Measurement and Interpretation', in P. Stoneman (ed.), *Handbook of Industrial Innovation*, Blackwell Press, London.

Pavitt, K. (1991a), 'What Makes Basic Research Economically Useful?', *Research Policy*, 20, pp. 109-119.

Pavitt, K. (1991b), 'The National Usefulness of the Science Base', paper presented to the Advisory Board of the Research Councils (ABRC), April.

Pavitt, K. (1995a), ‘National Policies for Technical Change: Where Are There Increasing Returns to Economic Research’, paper prepared for the Colloquium on Science, Technology and the Economy, organised by the US National Academy of Sciences at the University of California at Irvine.

Pavitt, K. (1995b), ‘Academic Research, Technical Change and Government Policy’, in J. Krige and D. Pestre (eds), *Science in the 20th Century*, Harwood Academic Publishers (forthcoming).

Popper, S. W. (1995), *Measuring the Economic and Social Benefits of Fundamental Science*, Critical Technologies Institute (MR-708.0-OSTP), Rand, Washington, D.C.

Porter, M. (1990), *The Competitive Advantage of Nations*, Harvard University Press, Cambridge, Mass.

Price, D. de Solla (1984), ‘The Science/Technology Relationship, the Craft of Experimental Science, and Policy for the Improvement of High Technology Innovation’, *Research Policy*, 13, pp. 3-20.

Prime Minister’s Science Council (1991), *Innovation in the Australian Science and Medical Instruments Industry*, Australian Government Publishing Services, Canberra.

Romer, P. M. (1992), ‘Two Strategies for Economic Development: Using Ideas and Producing Ideas’, in L. Summers (ed.), *Proceedings of the World Bank Annual Conference on Development Economics 1992*, World Bank, Washington, D.C.

Rosenberg, N. (1984), ‘The Commercial Exploitation of Science by American Industry’, paper presented at Harvard Business School’s 75th Anniversary Colloquium on Productivity and Technology, March 27-29.

Rosenberg, N. (1990), ‘Why Do Firms Do Basic Research (with Their Own Money)?’, *Research Policy*, 19, p. 165

Rosenberg, N. (1992), ‘Scientific Instrumentation and University Research’, *Research Policy*, 21, pp. 381-390.

Rosenberg, N. (1994) *Exploring the Black Box: Technology, Economics and History*, Cambridge University Press, Cambridge.

Rosenberg, N. and R. R. Nelson (1994), ‘American Universities and Technical Advance in Industry’, *Research Policy*, 23, pp. 323-348.

Rothwell, R. (1977), ‘The Characteristics of Successful Innovation and Technologically Progressive Firms’, *R&D Management*, 7, pp. 191-200.

Sanderson, M. (1972), *The Universities and British Industry, 1850-1970*, Routledge, London.

Scherer, F. M. (1982), ‘Inter-Industry Technology Flows in the United States’, *Research Policy*, 11, pp. 227-246.

Scotchmer, S. (1991), ‘Standing on the Shoulders of Giants: Cumulative Research and the Patent Law’, *Journal of Economic Perspectives*, 5, pp. 29-41.

Segal, N., R. Quince, and K. Wicksteed (1985), *The Cambridge Phenomenon: the Growth of High Technology Industry in a University Town*, Cambridge University Press, Cambridge.

Senker, J. (1991), ‘Evaluating the Funding of Strategic Science: Some Lessons from the British Experience’, *Research Policy*, 20, pp. 29-43.

Senker, J. (1992), ‘Relationships Between S&T Programme Outputs and Impacts: A Review of Small Country Experience’, a report prepared for EOLAS, The Irish Science and Technology Agency, Dublin.

Senker, J. (1995), ‘Tacit Knowledge and Model of Innovation’, *Industrial and Corporate Change*, 4, pp. 425-447.

Senker, J., P-B Joly, and M. Reinhart (1996), *Overseas Biotechnology Research in Europe’s Chemical/Pharmaceuticals Multinationals: Rationale and Implications,* Final Report for EC BIOTECH project PL945005 under the RTD programme, Scientific Studies on the Socio-Economic Impact of Biotechnology, Science Policy Research Unit, University of Sussex, Brighton.

Senker, J. M. and M. L Sharp (1988), *The Biotechnology Directorate of the SERC: Report and Evaluation of its Achievements, 1981-1987,* Report to the SERC Biotechnology Directorate, Science Policy Research Unit, University of Sussex, Brighton.

Sharp, M. (1993), *The Protein Engineering Club: An Assessment of the Club as an Experiment in Promoting a Programme of Strategic Research,* Report to the Biotechnology Directorate of the SERC, Swindon.

Sharp, M. (1995), ‘The Science of Nations: European Multinationals and American Biotechnology’, STEEP Discussion Paper No 28, Science Policy Research Unit, University of Sussex, Brighton.

Sharp, M, S. Thomas, and P. Martin (1993), *Technology Transfer and Innovation Policy: Chemicals and Biotechnology*, STEEP Discussion Paper No. 6, Science Policy Research Unit, University of Sussex, Brighton.

Sharp, M. and P. Patel (1996), ‘Europe’s Pharmaceutical Industry: An Innovation Profile’, Draft Report for the European Commission, Science Policy Research Unit, University of Sussex, Brighton.

Smith, K. (1991), *Economic Returns to R&D: Methods, Results, and Challenges*, Science Policy Support Group Review Paper No. 3, London.

Smith, K. (1995), ‘Interactions in Knowledge Systems: Foundations, Policy Implications and Empirical Methods’, *STI Review*, pp. 69-102 (OECD, Paris).

Stankiewicz, R. (1994), ‘Spin-off Companies from Universities’, *Science and Public Policy*, 21, pp. 99-107

Steinmueller, W. E. (1994), ‘Basic Research and Industrial Innovation’, Chapter 5 in M. Dodgson and R. Rothwell (eds), *The Handbook of Industrial Innovation, Edward Elgar, Aldershot.*

Sterlacchini, A. (1989), ‘R&D, Innovation, and Total Factor Productivity Growth in British Manufacturing’, *Applied Economics*, 21, pp. 1549-1562.

Stoneman, P. (1989), *Overseas Financing for Industrial R&D in the UK*, paper presented at Section F of the British Association for the Advancement of Science, Sheffield, 1989.

Taggart, J. H. (1989), ‘Determinants of the Foreign R&D Location Decision in the Pharmaceutical Industry’, University of Strathclyde Business School Working Paper 89/7, Glasgow.

Teich, A. H. (1986), *Support for Basic Research: a Review of the Federal Role, National Science Foundation, Washington, D.C.*

Teich, A. H. and K. M. Gramp (1988), *R&D in the 1980s: a Special report*, American Association for the Advancement of Science, Washington, D.C.

Thomas, L. G. (1994), ‘Implicit Industrial Policy: The Triumph of Britain and the Failure of France in Global Pharmaceuticals’, *Industrial and Corporate Change*, 3, pp. 451-490.

Van der Ven, A. H. and R Garud (1991), *Innovation and Industry Development: The Case of Cochlear Implants*, Strategic Management Research Centre, University of Minnesota.

R. Vernon (1966), ‘International Investment and International Trade in the Product Cycle’, *Quarterly Journal of Economics*, 80, pp. 190-207.

Vincenti, W. (1990), *What Engineers Know and How They Know It*, Johns Hopkins Press, Baltimore.

von Hippel, E. (1988), *The Sources of Innovation*, Oxford University Press, Oxford.

von Tunzelmann, N. (1995), *Innovation Trends in the Food-Processing Industry*, draft report for the EU European Information Monitoring System, Luxembourg.

von Tunzelmann, N. (1996), ‘Localised Technological Search and Multi-Technology Companies’, STEEP Discussion Paper No. 29, Science Policy Research Unit, University of Sussex, Brighton.

Webster, A. (1994), ‘University-Corporate Ties and the Construction of Research Agendas’, *Sociology*, 28, pp. 123-142.

Zucker, L. G. and M. R. Danby (1995), ‘Virtuous Circles of Productivity: Star Bioscientists and the Institutional Transformation of Industry’, NBER Working Paper 5342, Cambridge.

APPENDIX 2

A2. Recommendations for Future Research

In the original invitation to tender for this study, one of the objectives listed was to act as a scoping study for possible future research on the relationship between publicly funded basic research and economic performance. In what follows, we identify key issues that might benefit most from future research and suggest how they might best be approached.

1. Econometric studies

We would not advocate giving particularly high priority to econometric studies compared with theoretical work and empirical case studies and surveys. Nevertheless, there may be some merit in carrying out certain of the following:

- a Mansfield-type study in the UK (or, better still, a study comparing Britain with other leading European countries);
- research at more disaggregated levels focusing on sectors or firms (cf. Malerba, 1992, which is based on the Yale Survey data);
- developing and incorporating into econometric approaches a broader range of science and technology indicators;
- exploration of alternatives to the blunt production function approach (e.g. through systems or non-neo-classical procedures).

2. Theoretical analysis

The major theoretical challenges are:

- to devise a basis for public support for basic research that does not rely solely on the informational properties of its ‘output’, and which recognises that nation states live in an increasingly globalised world with open borders;
- to explore the argument, first advanced by de Tocqueville and Marx, that it is the dynamics of business firms that generate demands on the basic research system;
- to question the assumption (held, for example, by the ‘new growth’ theorists) that the main factor determining technology’s contribution to growth is the strength of spillovers.

3. Surveys and case studies

The main empirical requirements are for surveys and case studies that:

- systematically analyse the relationship between basic research and technology - in other words, studies to analyse and compare the various forms of links (based on the transfer of codified or tacit knowledge, people, instrumentation and so on) between basic research and technological practice, looking at how these vary with scientific field, sector of application, country and degree of internationalisation, as well as how they evolve over time;
- assess whether British firms’ weaknesses in sectors like electronics are having harmful effects on related fields in basic research, and the degree to which foreign firms establishing research laboratories in the UK can compensate for these deficiencies.

4. *Combining data with models*

Besides the theoretical and empirical studies proposed above, work is also needed that links the data to the theoretical models. Suggestions here include:

- using the SPRU innovations database to construct a sectoral input-output model for the UK (see Section 4.1 above);
- taking up the suggestion of Romer that what ‘new growth’ theory most needs at present is more inputs from case studies and data such as patent indicators;
- developing dynamic models to integrate the results of the various studies suggested above.