Pre-publication text

A report commissioned by CVCP and funded jointly by HEFCE (Higher Education Finding Council for England)

The Impact of Publicly Funded Research on Innovation in the UK

Report from
SPRU – Science and Technology Policy Research, University of Sussex

Ammon Salter, Pablo D'Este, Ben Martin, Aldo Geuna, Alister Scott, Keith Pavitt, Pari Patel, and Paul Nightingale

May 2000

SPRU Impact Policy 4.23.doc

Foreword

The results of the UK Government's Spending Review 2000 will be announced later this summer. In our submission to the spending review ('Investing in Universities and Colleges for Global Success', CVCP, December 1999) we set out our vision of the goals and priorities for UK higher education for the next three years. We pointed to the strengths and rich diversity of UK universities, and outlined a framework by which they could fulfil their role in the economic, social and cultural life of the nation.

We noted in our submission that Government had acknowledged the importance of university research and the exploitation of the knowledge it generates for national economic performance, and we welcomed the fact that science and research forms one of the cross-departmental themes of the spending review. We urged Government to find the substantial additional investment for universities to back up its priorities.

This report from SPRU, jointly funded by the Higher Education Finding Council for England, on the impact of public investment in basic research on innovation is timely. It supplements the case we made in our submission to the spending review. But it also stands in its own right as an overview of the increasing importance of university and other publicly funded research in driving competitiveness and building a knowledge-based economy.

The report analyses the UK's modest levels of investment in research by comparison with other countries, from which UK universities have nevertheless produced world-class outputs. It surveys the evidence for the substantial return on public funds that investment in university research delivers. The authors identify the multiple forms which that return takes, from start-up firms to the creation of new instrumentation and methods, from the development of networks to the flow of skilled people. On the basis of the evidence surveyed, they outline a number of implications for public policy, which will help stimulate debate.

Together with a parallel report from PREST at the University of Manchester, this report offers strong support for the CVCP case for additional Government investment in university research capacity. It also demonstrates the importance of a flourishing research base for national prosperity.

Professor Howard Newby
President, CVCP

Talent, not Technology: Publicly Funded Research and Innovation in the UK

Executive Summary

This report was commissioned from SPRU (Science and Technology Policy Research, University of Sussex) by the Committee of Vice-Chancellors and Principals (CVCP) as a supplement to its submission to the UK Government's second Comprehensive Spending Review, the results of which will be announced in summer of 2000. It is jointly funded by the Higher Education Funding Council for England (HEFCE). The report is an update of an earlier report written by SPRU for the UK Treasury in 1996.

This document is the summary of a more comprehensive report on the benefits of publicly funded research to innovation. The full report may be accessed on the SPRU website: http://www.sussex.ac.uk/spru/index.html.

This report focuses on publicly funded research and the need to strengthen it if the UK is to remain a world leading innovator in the 21st century. Research, innovation and economic performance are intimately linked in the knowledge-driven economy. Research expands our capabilities to solve technical and social problems and it underpins innovation within firms. Yet there is increasing evidence that the amount of support for public and private research in the UK has not been adequate. The report demonstrates that the UK has not kept pace with other OECD countries in its investment in research.

For the first time, this report brings together three crucial aspects of this debate. It examines the empirical evidence about the role of publicly funded research in innovation in the UK, it gives a comparison of the UK's research investment in relation to that of other leading countries, and it places this evidence in the context of an integrated research-innovation framework.

This report offers the following key insights:

- The UK research sector remains highly productive. However, there is a widening investment gap in research between the UK and the US and other leading OECD countries. For example, the UK spending per capita is less than half the amount spent by the United States on R&D conducted in higher education. This investment gap could undermine the UK's strength in research. Past success alone cannot guarantee the strength of the UK research base in an increasingly competitive world.

- The research capacity of the commercial sector is a crucial ingredient for enhancing the UK innovation system. The report shows that where firms in the UK invest in research and innovation, they are able to exploit the quality of the UK research base to support their innovative activities. Public investment in research can certainly complement private investment, but it cannot act as a substitute for it. There is strong evidence to show that the industrial capacity to exploit research in the UK has weakened in the 1990s, particularly in comparison to that in other countries and regions. This growing weakness in private R&D helps to undermine the ability for research to underpin innovation in the UK.

- The report explores the nature of the modern innovation process, locating the contribution of research to innovation. Research supports innovation through a series of channels. These are:
  - increasing the stock of useful knowledge;
  - supply of skilled graduates;
  - creation of new instrumentation and methods;
  - development of new networks;
  - enhancement of technological problem-solving capacity;
  - generation of new firms; and
  - provision of social knowledge.

- The report finds that innovation is becoming increasingly international in scope and that participation in networks of innovation requires substantial investment.

- Future policy should ensure that the UK has comparable per capita levels of support for research as other leading OECD countries. Policy-makers should also attempt to develop better indicators of the role of research in innovation; help to bridge the gap between research and practice; expand beyond publication metrics in their assessments and understanding of the impact of research; and use the research sector to promote talent rather than technology.

Setting the scene

This report was commissioned by the Committee of Vice-Chancellors and Principals (CVCP) as a supplement to its submission to the UK Government's second Comprehensive Spending Review, the results of which will be announced in summer of 2000. It is part funded by the Higher Education Funding Council for England (HEFCE). The report is an update of an earlier report written by SPRU (Science and Technology Policy Research) for the UK Treasury in 1996.

This document is the summary of a more comprehensive report on the benefits of publicly funded research to innovation. The full report may be accessed on the SPRU website: http://www.sussex.ac.uk/spru/index.html.

Considerable public funds are invested in research in the UK. Some might ask what impact does this funding have on innovation? Is research a good investment? What contribution does research funding make to society? Why should we continue to fund this activity when many other areas of public services are in crisis?

In this report, we offer a strategy for exploring these questions. We summarise what we know about the impact of publicly funded research in the UK. Current evidence is patchy, uneven and incomplete. The questions posed above require more and better evidence.

Traditionally, publicly funded research is seen as providing economically useful information for industry to exploit. Publicly funded research has been seen as the first stage in the process of innovation, a process leading from science to technology to market. This linear model was often a misleading simplification that directed attention away from the issues that have become more important over time. The relationship between publicly funded research and innovation is interactive and non-linear. Short, simplistic models of cause and effect are deeply misleading. Science often follows technology and the market often leads technology and science.

In order to construct a more useful picture of the way publicly funded research impacts on innovation, we develop a new approach to understanding publicly funded research and innovation drawing on current thinking. This new approach stresses the role of publicly funded research in expanding our capabilities to solve technical and social problems.

The report provides compelling evidence of an investment gap between the UK and leading OECD countries in their support for publicly funded research. We review the latest evidence on the impact of publicly funded research on innovation in the UK. We begin by locating research in the context of innovation, offering a new framework for understanding the impact of publicly funded research on innovation. We then explore the position of the UK vis-à-vis other OECD countries in investments in research and innovation. The report then focuses on the research system, its productivity and impact. Along the way, we explore the geography of innovation, and how we understand research and innovation within a global community. We end the report by offering guidelines for policy.

Understanding the link between research and innovation

Although innovation has risen to the top of the political agenda in many OECD countries, we still do not have an adequate model for understanding the link between publicly funded research and innovation (Freeman and Soete, 1997). The traditional view of the relationship between publicly funded research and innovation is based on a linear model (Bush, 1945). According to this model, public research produces economically useful information for firms to exploit. It sees science and research as the first mover in a process of articulation leading from idea to products. Publicly funded research creates new information that is economically useful and freely available to all firms. By increasing the funds for research, government expands the pool of economically useful information and therefore expands opportunities for innovation.

Although this model is now routinely acknowledged to be incomplete, it still holds sway over much thinking on this issue. Part of the problem is related to language. Our understanding of science and research is rooted to beliefs in social progress and the role of science in directing technological and social change. Yet, the linear model is inadequate for a full understanding of the process of innovation.

- It does not provide a satisfactory explanation of the processes by which publicly funded research contributes to economic growth.
- It exaggerates the importance of one nation 'free-riding' on the developments of another and encourages an (ultimately self-defeating) excessively nationalist approach to technological development (Ostry and Nelson, 1995).
- It reinforces a constricted view of the practical relevance of basic research by concentrating on direct (and more easily measurable) contributions, to the neglect of indirect ones.
- It cannot explain why some science and technology systems perform better than others, or why different organisations conducting similar research activities create different types of knowledge or are systematically different in their research productivity.

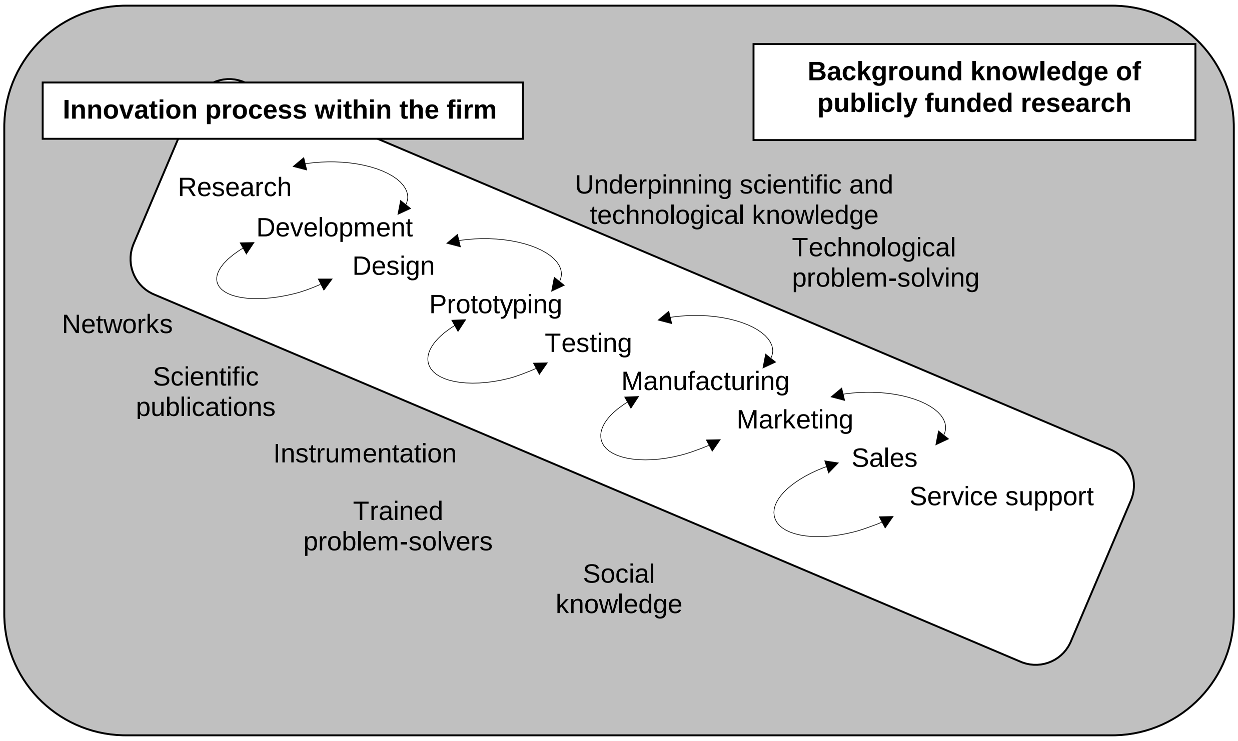
Some economists have recognised the importance of innovation and have attempted to develop models that take into account the role of innovation in growth. These models vary in their conclusions but all suggest that a key role is played by innovation in generating economic development (Grossman and Helpman, 1994; Romer, 1986 1994; Aghion and Howitt, 1995; Helpman, 1998). Yet these economic models remain limited in their treatment of innovation because they view innovation as an automatic by-product of certain activities, such as investments in education (for detailed discussion, see Verspagen 1993 and Nelson 1998). They fail to acknowledge the costs necessary for exploitation and assimilation of knowledge for innovation (Cohen and Levinthal, 1989).

More illumination is provided by penetrating the black box of the process of innovation. The approach used here draws together the various insights emerging from innovation studies (e.g. Rosenberg, 1982; Freeman and Soete, 1997). Innovation involves the successful commercial exploitation of new ideas. The innovation process itself is uncertain, complex, highly interactive, evolutionary and non-linear. It requires more than scientific knowledge and there is a long process of development from idea, to product/service, and then to the market. Innovation involves all these steps, as well as surprises, coincidences and unpredictable factors. For the successful development of an innovation, firms need to make systematic investment in the development of new ideas.

Firms do not innovate in isolation. Innovation occurs within international chains of activities. Firms are linked together in systems of interdependent networks of production and technology. In this respect, innovation is social in nature. Innovation involves many interactions between the different steps of the innovation process, between different organisations, and between different departments within the same firm (Lundvall and Borrás, 1997). Innovation is also cumulative. The state of technology determines the ability to adjust products and processes to new economic conditions (Dosi *et al*., 1988). Technological options are also constrained by the history of previous technical choices, giving rise to the phenomena of ‘path dependence’ and ‘lock-in’ (David, 1985).

The innovation process is driven by the activities of business firms (Figure 1). As Figure 1 shows, the innovation process takes place at many levels and draws from public research at each level in different ways. In some sectors, we find the link between new scientific research and development stage of the production process within the firm is quite strong. In other sectors, the research impacts indirectly through engineering knowledge and other factors.

Figure 1. The innovation process and publicly funded research as background



Three cross-cutting themes emerge as central to the analysis of the role of publicly funded research in innovation:

- Capability
- Variety
- Capacity.

These are now briefly explored in turn.

Research as capability

Our approach to the economics of publicly funded research suggests that a distinction needs to be made between information as a commodity and knowledge as the capability to use information. The view of publicly funded research as information substantially undervalues the extent to which knowledge and research skills are embodied in researchers and the institutional networks within which they conduct their work.

The view that disclosure is all that matters misrepresents the nature of the innovation process, implying that scientific knowledge is 'on the shelf, costlessly available to all comers' (Rosenberg, 1990). It fails to appreciate the extent to which scientific or technical knowledge requires a substantial capability on the part of the user – both in research and in the application of knowledge.

To paraphrase the OECD, information abounds – it is the *capability* to use it in meaningful ways that is in scarce supply (OECD 1992). Often this capability is expensive to acquire and maintain (Pavitt, 1998).

The new approach sees funding in research as an investment in the ability of society to explore and solve complex problems. Investments in publicly funded research expand the *learning capabilities* of a society. Even (or especially!) in the world of the internet, scientific information is only valuable to those with the skills to filter, apply, use and exploit it. The problem many firms face is too much information rather than too little (Wildavsky, 1983). It is the capability to understand, pattern and locate this information in the context of other activities that is often in short supply.

Supporting Variety

Public funding for research also plays an important role in supporting social and technological variety. This is the second cross-cutting theme of our approach to analysing the impact of publicly funded research on innovation.

Variety is a vital feature of flexible innovation systems. Through government funding for research, it is possible to create diverse novel approaches to resolving technological challenges by increasing the variety of scientific options available to firms.

Many social and technical issues involve choices between competing technical options. Public policy debates are increasingly focused around the risks and uncertainties associated with different options. One of the reasons that risk issues have become more important is that once a particular technological path has been chosen, a host of self-reinforcing mechanisms come into play. Investments in social, technological and financial resources can render these technical choices effectively irreversible (David, 1985; Arthur, 1983; Stirling and Mayer, 1999).

Government funding for research can help limit these irreversibilities, offering new options in technological systems. The market, by contrast, tends to 'use up' the existing sources of variety, leading to convergence and irreversibility, and locking society into particular paths. Government action is sometimes required to break this tendency toward ‘lock in’.

Knowledge as capacity

The third cross-cutting theme in the new approach is capacity. If capability is the qualitative measure associated with person-embodied research skills, and variety is a measure of the diversity of the options within an innovation system, capacity is more of a quantitative measure that encapsulates the size of the investment needed in all parts of the innovation system for it to be able to make the most of the capabilities and variety within it.

In an influential study, Cohen and Levinthal (1989) suggest that R&D undertaken within firms has two functions: it allows firms to create new knowledge, but it also enhances their ability to assimilate and exploit existing external knowledge. They refer to this second dimension as the firm’s ‘absorptive capacity’.

From this and other research it is clear that capacity is a function of at least three factors:

- internal capabilities
- the breadth of necessary expertise, and
- the ability to communicate across institutional boundaries.

This need for capability shows that while public investment in research can certainly complement private investment, it cannot act as a substitute for it. Investments will only be translated into innovative products and services if there is the absorptive capacity within industry. There is significant ‘two-way’ interaction between universities and industry (see Meyer-Kramer and Schmoch, 1998; Narin *et al.*, 1997). The evidence shows that, where UK industry is strong, the impact of publicly funded research is greatest. The commercial sector in the UK needs to invest more in research if it is to have the internal capability and breadth to benefit from public sector research.

In summary, these themes of capability, variety and capacity provide an approach for considering the benefits of public sector research for innovation. They also provide a starting point for discussing the scale and types of investment required in the research system.

The UK Research Base in a Globalising World

The key element of this report has been to explore the empirical evidence on the UK's investment in innovation and research in comparison to other OECD countries. This work has been comparative and relies on the latest available data sources. In this section, we highlight the main findings of this comprehensive empirical analysis. Further information about the data and the empirical analysis are available in the full report.

Table 1
Productivity of science systems by papers by funding, citations by funding and papers per researcher, 1997

	Papers per $ Million[1]	Rank	Citations per $ Million[2]	Rank	Papers per Researcher[3]	Rank
Czech Republic	36.7	1	75.2	3	3.4	23
Hungary	25.4	2	66.3	6	4.0	22
New Zealand	24.9	3	76.0	2	10.6	8
Poland	17.9	4	39.4	15	2.1	24
Denmark	16.5	5	76.7	1	11.8	4
Greece	16.4	6	36.5	18	4.2	21
United Kingdom	**16.0**	**7**	**70.5**	**4**	**11.2**	**6**
Finland	15.6	8	67.2	5	11.9	3
Canada	14.7	9	61.0	8	10.9	7
Australia	13.9	10	48.3	13	10.2	9
Ireland	12.9	11	38.2	17	7.0	17
Iceland	12.7	12	54.6	9	8.8	13
Spain	12.1	13	36.3	19	5.2	19
Sweden	11.3	14	52.3	10	15.7	1
Switzerland	10.9	15	65.7	7	15.3	2
Netherlands	10.3	16	48.7	12	11.3	5
Norway	10.0	17	35.1	20	9.5	11
France	9.8	18	38.3	16	8.4	14
Belgium	9.5	19	41.3	14	9.9	10
United States	9.2	20	49.0	11	9.2	12
Italy	9.0	21	34.0	21	5.6	18
Germany	7.9	22	31.9	22	7.2	16
Portugal	7.2	23	17.9	24	1.8	25
Austria	7.1	24	25.9	23	7.3	15
Japan	3.6	25	11.7	25	4.5	20
Turkey	3.3	26	4.2	27	0.7	26
Mexico	3.2	27	6.5	26	0.4	27

Source: Katz, 2000 - taken from OECD, Main Science and Technology Indicators, OECD Statistics, 1999 and ISI National Science Indicators on Diskette
1. This number refers to higher education R&D expenditures in 1997 in $ dollar PPP.
2. This number refers to number of citations per paper from ISI National Science Indicators on Diskette
3. This number refers to number of papers per researcher, OECD sources.

The main points to emerge from the empirical analysis were:

- The UK research sector remains highly productive. Regardless of the indicator used, the UK is among leaders of OECD countries in publications. For example, among OECD countries, the UK receives among the highest number of publications per millions of pounds of funding in higher education R&D. The number of citations per unit of funding is also high in the UK (see Table 1).

- The UK research sector is strong across a large number of areas. Of the 152 fields of research, the UK is a world leader in 26 fields. In most areas of research, the scientific papers by UK academics remain among the most highly cited.

Table 2
Higher Education Expenditures on R&D (HERD)[1] per capita
(PPP $, constant prices, 1990)[2]

Countries[3]	1986	Rank	1992	Rank	1997	Rank	Compound annual growth rate %[4] 1992-97	1986-1997	Rank
Sweden	141	1	139	1	144	1	1.0	0.2	20
Switzerland	72	4	136	2	135	2	-0.3	6.5	6
Austria*	71	5	89	6	111	3	5.7	5.7	9
Netherlands	71	6	98	4	105	4	1.8	4.1	12
US	79	3	89	5	97	5	1.6	1.9	17
Norway	61	9	86	7	96	6	2.7	4.6	11
Finland	50	13	69	11	93	7	6.2	5.8	8
Japan	81	2	102	3	82	8	-4.2	0.1	21
Australia	51	11	67	12	82	9	4.9	4.8	10
Denmark	51	12	66	14	79	10	3.6	4	13
Belgium	44	15	73	8	75	11	1.0	6.1	7
Iceland	n/a	22	67	13	74	12	2.0	n/a	n/a
Germany[5]	61	8	71	10	72	13	0.3	1.5	18
France	53	10	65	15	71	14	1.8	2.7	15
Canada	63	7	71	9	66	15	-1.5	0.4	19
UK	**48**	**14**	**55**	**16**	**65**	**16**	**3.3**	**2.7**	**16**
Italy	32	16	44	17	49	17	2.1	3.9	14
Ireland	16	18	29	20	47	18	10.3	10.4	4
New Zealand	25	17	40	18	43	19	2.3	8.9	5
Spain	11	19	32	19	37	20	3.1	11.6	2
Korea	n/a	n/a	n/a	n/a	36	21	n/a	n/a	n/a
Portugal	9	20	27	21	30	22	1.7	11.1	3
Greece	5	21	12	22	21	23	15.3	17.1	1

Notes
1. HERD is intended to describe the characteristics and trends of R&D in the Higher Education sector, which includes all universities, colleges of technology and other institutes of post-secondary education and also all research institutes, experimental stations and clinics operating under the direct control of, or administered by, or associated with higher education establishments.
2. Higher Education Expenditure on R&D (HERD) data, provided at current national currency, have been deflated using the implicit GDP Price Indices (1990 as base year) for each country, and then converted to US$ using purchasing power parities (PPP).
3. Due to incomplete series provided by the OECD along the period, the ratios and the growth rates for some countries have been computed taking the following time periods: Australia (1986-1996), Belgium and Greece (1986-91, 1991-1995), Iceland (1987-1997), Netherlands (1986-1996), Switzerland (1987-1996), Sweden and Norway (1987-1993, 1993-1997), N.Zealand (1989-1995). For Austria, it has been assumed that the compound annual growth rate of HERD per capita for the period 1989-93 (5.7%), for which data on HERD is provided by the OECD, remains the same for the following sub-period (1993-1997). According to this assumption, the value of the ratio for 1997 has been computed.
3. Compound annual growth rate 'r' has been computed as: $r = (X_{t+n}/X_t)^{1/n} - 1$
4. The data cover western Germany only until 1990, and Unified Germany from 1991.
Source: Main Science and Technology Indicators. OECD Statistics. 1999, 1995 and 1992.

- The past strength of the UK research system should not be taken for granted. Small European countries, such as Denmark and Finland, have made substantial investments in research and these investments have been translated into high quality research. The position of the UK could reflect past investment levels and the next generation of UK researchers, who are comparatively under-funded, may not be able to sustain this record of excellence.

- The performance of the UK research base is even more remarkable given the gap in funding between the UK and other OECD countries. The UK investments in higher education R&D have not kept pace with other OECD countries. The UK has the 16th lowest growth rate in higher education R&D among the leading twenty-one OECD countries (see Table 2).

Table 3
Gross expenditure on R&D (GERD) per capita

(PPP $, constant prices, 1990)[1]							Compound average annual growth rate (%)[3]		
Counrties[2]	1986	Rank	1992	Rank	1997	Rank	1992-97	1986-1997	Rank
US	579	1	608	1	673	1	2.1	1.4	14
Sweden	490	3	539	4	669	2	5.5	3.2	10
Japan	405	5	548	2	573	3	0.9	3.2	9
Switzerland	558	2	546	3	554	4	0.3	-0.1	19
Finland	241	12	313	10	466	5	8.3	6.2	4
France	351	6	423	5	410	6	-0.6	1.4	15
Germany[4]	452	4	409	6	397	7	-0.6	-1.2	21
Denmark	211	13	291	11	383	8	5.6	5.5	6
Netherlands	321	8	325	8	368	9	3.2	1.4	16
Norway	287	9	315	9	359	10	3.4	2.3	11
Korea	n/a	n/a	182	18	340	11	13.4	n/a	n/a
UK	**336**	**7**	**327**	**7**	**327**	**12**	**0.0**	**-0.2**	**20**
Australia	193	14	258	14	308	13	4.5	4.7	7
Canada	263	10	275	13	307	14	2.2	1.4	17
Iceland	117	18	220	16	289	15	5.5	8.6	2
Austria	193	15	252	15	280	16	2.1	3.5	8
Belgium	241	11	276	12	277	17	0.1	1.6	13
Ireland	75	19	128	20	251	18	14.4	11.6	1
Italy	161	16	197	17	188	19	-1.0	1.4	18
New Zealand	121	17	129	19	138	20	2.3	2.3	12
Spain	60	20	110	21	114	21	0.6	6.0	5
Portugal	31	21	64	22	73	22	2.7	8.1	3
Greece	23	22	44	23	n/a	n/a	n/a	n/a	n/a

Notes:
1. Gross Domestic Expenditure on R&D (GERD) data, provided at current national currency, have been deflated using the implicit GDP Price Indices (1990 as base year) for each country, and then converted to US$ using purchasing power parities (PPP).
2. Due to broken series in information provided by the OECD along the period, the growth rates for some countries have been computed taking slightly different time periods: Australia (1986-1996), Belgium (1986-1990, 1990-1995), Greece (1986-1993), Netherlands (1986-1996), New Zealand (1989-1995), Norway and Sweden (1987-1993, 1993-1997), and Switzerland (1986-1996).
3. Compound annual growth rate 'r' has been computed as: $r = (X_{t+n}/X_t)^{1/n} - 1$
4. The data cover western Germany only until 1990, and Unified Germany from 1991.

Source: Main Science and Technology Indicators. OECD Statistics. 1999, 1995 and 1992.

- Gross expenditures in R&D in the UK have remained stagnant since the mid-1980s. The UK has the slowest rate of growth in the OECD in R&D expenditures and the gap between the UK and the leaders in the OECD is increasing. In terms of civil R&D budget expenditures on R&D, the UK spends less than half as much as OECD leaders and this gap is also escalating (see Table 3).

- The research capacity of the commercial sector is a crucial ingredient in enhancing the UK innovation system. There is compelling evidence that the industrial capacity to exploit research in the UK is weak, especially in comparison to other OECD countries. The UK spends half as much as Sweden and the US per capita on business R&D and the gap between the UK and the leading OECD countries is increasing. This weakness undermines the ability for research to underpin innovation.

Table 4
Business Enterprise Expenditure on R&D[1] per capita
(PPP $, constant prices, 1990)[2]

							Compound annual Growth rate %[4]		
Countries[3]	1986	Rank	1992	Rank	1997	Rank	1992-97	1986-1997	Rank
Sweden	327	4	375	4	501	1	7.5	4.4	8
US	418	2	437	1	500	2	2.7	1.6	13
Japan	269	5	377	3	413	3	1.8	3.9	9
Switzerland	434	1	383	2	391	4	0.5	-1.0	20
Finland	142	11	178	9	308	5	11.6	7.3	2
Germany[5]	331	3	281	5	268	6	-0.9	-1.8	21
France	206	7	264	6	253	7	-0.9	1.8	12
Korea	n/a	n/a	n/a	n/a	247	8	n/a	n/a	n/a
Denmark	117	14	170	10	239	9	7.1	6.7	4
UK	**223**	**6**	**219**	**7**	**213**	**10**	**-0.5**	**-0.4**	**18**
Netherlands	188	8	159	12	208	11	5.6	0.9	15
Norway	178	9	168	11	205	12	4.9	1.4	14
Canada	142	12	149	13	195	13	5.5	2.9	10
Belgium	174	10	184	8	187	14	0.3	0.7	16
Ireland	40	17	84	17	185	15	17.2	14.8	1
Austria[6]	129	13	142	14	157	16	2.5	2.5	11
Australia	73	16	114	15	146	17	6.4	7.1	3
Iceland	n/a	n/a	48	19	104	18	16.6	n/a	n/a
Italy	94	15	110	16	101	19	-1.7	0.6	17
Spain	33	19	56	18	56	20	-0.1	4.7	7
New Zealand	39	18	35	20	37	21	2.1	-0.7	19
Portugal	8	20	14	21	16	22	3.3	6.5	5
Greece[7]	7	21	9	22	13	23	6.5	6.5	6

Notes:
1. Business enterprise R&D expenditures covers R&D activities carried out in the business enterprise sector by performing firms, regardless of the origin of funding; therefore, the business enterprise sector covers private and public enterprises and institutes serving such enterprises.
2. Business Enterprise Expenditure on R&D (BERD) data, provided at current national currency, have been deflated using the implicit GDP Price Indices (1990 as base year) for each country, and then converted to US$ using purchasing power parities (PPP).
3. Due to incomplete series provided by the OECD along the period, the ratios and the growth rates for some countries have been computed taking the following time period: Australia (1986-1996), Belgium and Greece (1986-91, 1991-1995), Iceland (1987-1997), Switzerland (1987-1996), Sweden and Norway (1987-1993, 1993-1997), N.Zealand (1989-1995).
4. Compound annual growth rate ‘r’ has been computed as: $r = (X_{t+n}/X_t)^{1/n} - 1$
5. The data cover western Germany only until 1990, and unified Germany from 1991.
6. For Austria, it has been assumed that the compound annual growth rate of BERD per capita for the period 1989-93 (1.6%), for which data on BERD are provided by the OECD, remains the same for the following sub-period (1993-1997). According to this assumption, the value of the ratio for 1997 has been computed.
7. For Greece, it has been assumed that the compound annual growth rate of BERD per capita for the period 1989-93 (6.9%), for which data on BERD are provided by the OECD, remains the same for the following sub-period (1993-1997). According to this assumption, the value of the ratio for 1997 has been computed.
Source: Main Science and Technology Indicators. OECD Statistics. 1999, 1995 and 1992.

- The 1990s were a lost decade for UK private investment in R&D. Both France and Germany suffered from a similar malaise. The weak R&D record of Germany and France over this period is hardly surprising, however, given each country's poor economic performance. Several factors explain their poor performance, such as the integration of East Germany into Germany and the entry conditions of the Euro. Yet in the UK, the years from 1992 to 1997 were a period of considerable economic expansion. In the UK this round of economic expansion did not lead to expansion in private R&D. This suggests that economic growth alone will not be able to expand the capabilities of the UK to exploit the research base for innovation (see Table 4).

- We contest the suggestion that the UK could become the California of Europe (Freedland, 1998). California spends almost four times as much as the UK on business R&D. If the UK were a US State, then it would be on par with Virginia and Oregon, hardly the most innovative of States (see Table 5).

- In terms of innovation expenditures, the UK is near the average of the European Union.

- Innovation surveys show that close to 50 per cent of firms in the UK cited universities as a source of information for innovation. Foreign firms use universities as a source of information for innovation more than domestic firms. Size also matters. The larger the firm the more likely it is that it will use universities as a source of information for innovation (see Table 6).

- The employment of scientists and engineers in UK industry as a percentage of the labour force is declining in the UK and the relative position of the UK among OECD countries is slipping (see Table 7).

Table 5
Business Expenditures on R&D and Higher education expenditures on R&D per capita, 1995 for US States, France, Germany and United Kingdom
(constant, $ 1990) [1]

	BERD	Rank	HERD	Rank	Population (millions)
Delaware	1313	1	65	34	0.7
Michigan	1123	2	68	31	9.7
Massachusetts	1071	3	216	3	6.1
District of Columbia	1068	4	288	2	0.6
Connecticut	1048	5	101	10	3.3
New Jersey	901	6	63	37	8.0
California	798	7	138	5	31.5
New Mexico[2]	761	8	697	1	1.7
Washington	692	9	78	24	5.4
Idaho	622	10	44	47	1.2
Minnesota	501	11	64	35	4.6
Rhode Island	460	12	94	12	1.0
Colorado	437	13	122	6	3.7
Illinois	426	14	117	7	11.9
New York	417	15	96	11	18.2
Indiana	411	16	57	41	5.8
Pennsylvania	388	17	85	16	12.0
Vermont	372	18	81	21	0.6
New Hampshire	361	19	71	27	1.1
Utah	356	20	89	15	2.0
Missouri	333	21	65	33	5.3
Germany[3]	**332**	**22**	**91**	**14**	**81.7**
Ohio	314	23	50	44	11.2
France	**309**	**24**	**85**	**17**	**58.1**
Iowa	308	25	109	8	2.8
Texas	291	26	69	29	18.7
Wisconsin	291	27	81	22	5.1
Arizona	276	28	93	13	4.3
North Carolina	271	29	84	19	7.2
Florida	253	30	35	50	14.2
Virginia	209	31	69	28	6.6
United Kingdom	**208**	**32**	**61**	**39**	**58.6**

Business Expenditures on R&D and Higher education expenditures on R&D per capita, 1995
for US States, France, Germany and United Kingdom
(constant, $ 1990) [1]

	BERD	**Rank**	**HERD**	**Rank**	**Population (millions)**
Oregon	207	33	72	26	3.1
Maine	202	34	23	54	1.2
Kansas	193	35	61	38	2.6
Maryland	187	36	202	4	5.0
Nevada	185	37	50	45	1.5
South Carolina	175	38	52	43	3.7
Tennessee	168	39	53	42	5.2
Georgia	143	40	80	23	7.2
Alabama	141	41	69	30	4.3
West Virginia	117	42	41	48	1.8
Kentucky	103	43	31	52	3.9
Nebraska	80	44	84	18	1.6
Oklahoma	77	45	50	46	3.3
Arkansas	64	46	31	51	2.5
Wyoming	46	47	73	25	0.5
Alaska	44	48	105	9	0.6
South Dakota	23	49	25	53	0.7
Mississippi	21	50	37	49	2.7
Montana	17	51	68	32	0.9
North Dakota	16	52	82	20	0.6
Louisiana	12	53	64	36	4.3
Hawaii	10	54	58	40	1.2

Notes:
1. Business Enterprise Expenditure on R&D (BERD) data and Higher Education Expenditure on R&D (HERD), provided at current national currency, have been deflated using the implicit GDP Price Indices (1990 as base year) for each country and US-States, and then converted to US$ for France, Germany and UK using the exchange rates to dollar of 1990. Implicit GDP Price indices, and population for each country and US-State are provided by the Main Science and Technology Indicators, and by the US Census Bureau, in the case of US-States.
2. New Mexico contains a large US nuclear facility at Los Alamos.
3. Germany includes the former East Germany

Sources: Science and Engineering Indicators, 1998 (National Science Foundation, US); Population Estimates Program, (US.Census Bureau); Main Science and Technology Indicators (OECD), 1999.

Table 6
Cumulative percentage of UK firms that ranked universities as an important source of information by industry
(1-2-3 likert scale)

Industries	Percentage of firms ranking universities as somewhat important	Percentage of firms ranking universities as important	Percentage of firms ranking universities as very important	Percentage of firms with formal collaboration with universities
Food, beverages and tobacco	39.2	15.0	1.7	14.2
Textiles, clothes and leather	35.0	12.5	0.0	10.0
Wood and paper	37.5	8.0	1.1	5.7
Publishing	27.5	7.5	0.0	11.3
Chemicals, rubber and plastics	58.7	24.3	6.9	13.2
Fabricated metal products	36.3	15.3	4.0	8.9
Machinery and equipment	53.5	28.3	4.7	11.0
Office machinery and computers, electrical machinery and radio, television and communication	58.4	20.8	7.3	11.8
Motor vehicles and other transport	55.0	21.4	5.7	10.0
All manufacturing industries	47.1	18.4	4.1	11.0

Source: UK Community Innovation Survey, Department of Trade and Industry, with permission.

Table 7

Total R&D scientists and engineers (or university graduates)[1] per thousand labour force

Countries	1986	Rank	1992	Rank	1997	Rank	Average annual growth rate %[10] 1986-1992	1992-1997	1986-1997	Rank
Japan	8.1	1	9.5	1	9.2	1	2.6	-0.6	1.1	14
Sweden[2]	5.0	3	5.9	5	8.6	2	2.3	6.4	4.6	4
Finland[3]	4.1	12	5.5	8	8.3	3	7.1	7.3	7.6	1
US[4]	7.4	2	7.5	2	7.6	4	0.3	n/a	n/a	n/a
Norway[2]	4.7	5	6.3	3	7.6	5	4.2	3.1	4.0	5
Australia[5]	4.6	6	6.0	4	6.6	6	4.5	2.4	3.6	8
France[5]	4.4	8	5.6	7	6.1	7	4.1	2.1	3.3	9
Denmark	3.3	14	4.4	13	5.9	9	4.9	6.0	5.4	2
Germany[6]	5.0	4	5.9	6	5.9	8	2.3	0.0	1.5	13
Ireland	3.0	15	4.1	15	5.7	10	11.6	7.4	5.3	3
Switzerland[5]	4.4	9	4.5	11	5.5	11	0.3	5.1	2.2	10
Canada[7]	4.4	10	4.8	9	5.4	12	1.4	4.0	2.0	11
Belgium[8]	3.8	13	4.3	14	5.3	13	2.5	5.3	3.7	6
UK[5]	**4.6**	**7**	**4.6**	**10**	**5.1**	**14**	**0.0**	**3.4**	**1.1**	**15**
Netherlands[9]	4.2	11	4.5	12	4.6	15	0.8	0.7	0.8	16
Austria[4]	2.3	18	3.4	17	4.1	16	5.0	n/a	n/a	n/a
New Zealand	2.8	16	3.6	16	3.5	17	8.7	-0.9	3.7	7
Italy[5]	2.8	17	3.0	18	3.3	18	1.1	2.4	1.6	12

Notes:

1. This category embraces the persons who actually create the new scientific knowledge and conceive and design the new products and processes. They normally work as directors, instructors, guides and supervisors of R&D programmes. (Proceedings of the Second Frascati conference on OECD international standards for the measurement of R&D, 1968, pag.77).

2. The periods for Sweden and Norway are: 1987-1993-1997, instead of 1986-1992-1997.

3. The periods for Finland are: 1987-1991-1997 instead of 1986-1992-1997.

4. In the cases of US and Austria, where there is no information from 1993 onwards, the data corresponding to 1997 has been estimated by extrapolating from the trend of growth obtained in the period 1986-1991 for US, and the period 1985-93 for Austria.

5. The periods for Australia, France, Italy, Switzerland and UK are: 1986-1992-1996 instead of 1986-1992-1997.

6. The periods for Germany are: 1987-92-95 instead of 1985-1992-1997. The data cover western Germany only until 1990, and Unified Germany from 1991.

7. The periods for Canada are: 1986-1992-1995 instead of 1986-1992-1997.

8. The periods for Belgium are: 1986-1991-1995 instead of 1986-1992-1997.

9. The periods for Netherlands are: 1985-1993-1996, instead of 1986-1992-1997.

10. Compound annual growth rate ‘r’ has been computed as: $r = (X_{t+n}/X_t)^{1/n} - 1$. This growth rate has been computed for each country according to their respective periods (for which data is provided).

Source: Main Science and Technology Indicators. OECD Statistics. 1999, 1995 and 1992.

- There has been a fall in the number of applications to UK courses in science and engineering. Women continue to be poorly represented in engineering and technology courses.

- Foreign students have helped to make up the shortfall in UK applications in engineering and technology, but too few of these students are staying in the UK after their education. This represents a major loss to UK industry's innovative potential.

The evidence presented above offers a fairly bleak picture of the UK situation. In both the public and private sectors, there has been decline in the UK's relative position in comparison to other leading OECD countries. Other OECD countries have made substantial investments in research, investments not yet matched in the UK in either the public or the private sectors. The overall picture of stagnant levels of employment of scientists and engineers and a fall in the number of applicants to science and engineering courses in the UK suggests that these trends will not be easy to overcome.

Despite the paucity of funding for R&D, the UK research system continues to perform well. Whatever measurement system used, the UK is among the world leaders in many different scientific and technological fields. This excellence has been maintained over a long period of time.

The data suggest that the UK received an excellent rate of return on its funding in research. The mismatch between the excellence of the publicly funded research system and the weakness of the private sector suggests that problems in the UK innovation system do not lie solely with the publicly funded sector. The impact of publicly funded research on innovation is through the use made of research within the innovation process of firms. Where firms lack the capability to make use of research, the impact of publicly funded research on innovation in general is severely curtailed. Greater efforts are necessary to ensure that firms in the UK have the capacity to access the high quality UK research base. Nevertheless, despite the weakness of UK firms in this respect, the UK research base continues to attract world-class firms and therefore plays a key role in generating inward investment into the country.

The returns on publicly funded research

What is the rate of return to public investment in research? Economists have attempted to estimate the private and social rates of return to private and publicly funded R&D – i.e. the monetary return from an investment in research. Most of the studies found a rate of return falling in the range between 20 and 50 per cent (see Table 8).

In general, these studies have been successful in generating a figure, but the value of these figures is of relatively limited use for policy-makers. There are several reasons for this:

- they provide an average not marginal rate of return; that is, they do not provide an estimate of the extra benefit of increased funding;
- most studies have focused on government R&D projects rather than research;
- they have tended to explore relatively 'successful' government R&D programmes, especially in agriculture, assuming no alternative method could have generated the economic returns associated with the products and processes attributed to the basic research in question (David *et al*., 1992);
- tracing the benefits of a particular project involves looking retrospectively at a technology, and does not take into account investments in complementary assets needed to bring the technology to market (Teece, 1986); and
- they do not reveal how the economic returns of basic research are actually realised.

Table 8
Rates of Return to Private and Publicly Funded R&D

Estimates of Private and Social Rates of Return to Private R&D Spending		
Studies	Private Rate of Return (%)	Social Rate of Return (%)
Minnasian (1962)	25	-
Nadiri (1993)	20-30	50
Mansfield (1977)	25	56
Terleckyj (1974)	27	48-78
Sveikauskas (1981)	10-23	50
Goto & Suzuki (1989)	26	80
Mohnen & Lepine (1988)	56	28
Bernstein & Nadiri (1988)	9-27	10-160
Scherer (1982 & 1984)	29-43	64-147
Bernstein & Nadiri (1991)	14-28	20-110
Estimates of Rates of Return to Publicly Funded R&D		
Studies	Subject	Rate of Return to Public R&D (%)
Griliches (1958)	Hybrid corn	20-40
Peterson (1967)	Poultry	21-25
Schmitz-Seckler (1970)	Tomato harvester	37-46
Griliches (1968)	Agricultural research	35-40
Evenson (1968)	Agricultural research	28-47
Davis (1979)	Agricultural research	37
Evenson (1979)	Agricultural research	45
Davis & Peterson (1981)	Agricultural research	37
Huffman & Evenson (1993)	Agricultural research	43-67

Source: Griliches (1995, p. 72) and OTA (1986).

The best study in this area was done by Mansfield. He focused on 'recent' academic research - i.e. research within 15 years of the innovation under consideration (Mansfield, 1991). Using a sample of 76 US firms in seven industries, he obtained estimates from company R&D

managers about what proportion of the firms' products and processes over a ten-year period could not have been developed without the academic research.

He found that 11 per cent of new products and 9 per cent of new processes could not have been developed without a substantial delay in the absence of the academic research, these accounting for 3 per cent and 1 per cent of sales respectively. He also measured those products and processes developed with 'substantial aid' from academic research over the previous 15 years; 2.1 per cent of sales for new products and 1.6 per cent of new processes would have been lost in the absence of the academic research. Using these figures, Mansfield estimated the rate of return from academic research to be 28 per cent (*ibid.*, p. 10).

In 1998, Mansfield published the results of a follow-up study. He found that:

- academic work was becoming increasingly important for industrial activities;
- 15 per cent of new products and 11 per cent of new processes could not have been developed (without a substantial delay) in the absence of academic research;
- innovations that could not have developed without academic research accounted for 5 per cent of total sales for the firms; and
- the time delay from academic research to industrial practice has shortened from seven years to six.

Beise and Stahl (1999) have replicated Mansfield's survey in Germany with a much larger sample of 2300 manufacturing firms. They found:

- 5 per cent of new product sales could not have been developed without academic research.
- research has a greater impact on new products than new processes
- small firms are less likely to draw from universities than large firms (*ibid.,* p. 409).

There is no UK equivalent of these studies. However, the lesson from these studies is that academic research can play a significant role in innovation. Although the exact figures are open to question, the findings of these studies show that with careful research it is possible to identify returns to publicly funded research. Many firms acknowledge the link between their new products and processes and publicly funded research. They see publicly funded research as important not only for underpinning the knowledge base of their firm's technological activities, but also as a source of new ideas for innovative products and processes.

The geography of innovation

Technological activities are increasingly international. Yet location still matters in determining patterns of innovation. For example, R&D is still highly geographically concentrated (Patel and Pavitt, 1995). Why is this so? Globalisation is often linked to localisation. Firms do go outside their local regions for new ideas, technologies and skills, but as they do so they often rely on a local infrastructure to support their research activities. One of the reasons for continued localisation is the need to keep at home a critical mass of R&D. This critical mass of skills allows firms to build linkages between domestic business and academic research. These links are often built over a long time period and depend on webs of personal contacts and face-to-face interaction (Patel and Pavitt, 1995).

The geography of innovation is also increasingly influenced by knowledge spillovers. The notion of a 'spillover' refers to the fact that firms may benefit from the R&D efforts of other firms or institutions in the vicinity that are conducting research in related scientific or technological fields. Firms can thus gain these benefits without having to pay for them. In this sense, they can be seen as ‘something for nothing’.

Narin *et al.* developed an approach for exploring spillovers from publicly funded research to innovation, based on analysing scientific publications cited in US patents. They explored the sources of research support acknowledged in the citations to scientific papers. They found:

- an increasing number of scientific references cited in industrial patents (over a six-year period, there has been a tripling in the number of citations to academic research in US patents);
- industrial innovation is becoming more and more dependent on academic research; and
- US industry relies on the results from publicly funded research for innovation.

Studies of the economic geography of innovation also stress the importance of location and geographical agglomerations. Studies of Silicon Valley (in Northern California) and the ‘Route 128’ area in Massachusetts have found that local institutions (including the research infrastructure) profoundly shape a region’s capacity to innovate (Storper, 1997; Saxenian, 1994). The development of geographical agglomerations is a result of the person-embodied nature of much technological knowledge and the consequent importance of face-to-face interactions. Since these personal interactions are essential to deal with the uncertainty inherent in the future development of technologies or markets, firms and individuals tend to cluster.

All this suggests that each nation or region needs to maintain its own capability in research and development. Personal links and face-to-face interactions are essential not only for the research process but also for sharing and transferring knowledge quickly and effectively. Policies designed to support geographical agglomeration should help facilitate this interaction (Wolfe, 1996; Cooke and Morgan, 1998).

Spillovers cannot by themselves overcome under-investment. Where there are substantial investments in knowledge creation, such as R&D, spillovers can enhance and supplement the benefits of investments in innovation. Spillovers complement rather than replace individual investment. In order to gain the benefits from the work of others, firms and nations need to make considerable investments themselves. There are no ‘free lunches’ for innovative firms or countries.

The seven benefits of research

In this section, we explore the mechanisms that link publicly funded research and innovation. As has already been suggested, investments in research are investments not simply in the creation of new information but in expanding the capabilities of a society to solve complex problems and generate wealth. Our approach explores the detailed mechanisms of how this comes about.

On the basis of this approach, we outline the seven benefits of public funding for research, drawing from the extensive literature on this issue in the academic and industrial community. These main benefits to research funding are:

- Increasing the stock of useful knowledge
- Training skilled graduates

- Supporting new professional networks and stimulating social interaction
- Expanding the capacity for technological problem-solving
- Producing new instrumentation and methodologies
- Creating new firms
- Provision of social knowledge

Increasing the stock of useful knowledge

Although we have noted that publicly funded research produces benefits well beyond the production of new knowledge, this is still one of its fundamental benefits for innovation. The literature identifies two types of research-based knowledge: codified and tacit. Codified knowledge is that which comes in a written form; it is the more visible of the two. Tacit knowledge refers to the skills, intelligence and experience brought to any task by those that carry it out. This distinction can help in analysing the value of publicly funded research, as we shall show.

Many studies support the idea that publicly funded research produces useful knowledge of both kinds. Some of the features of the direct use of new knowledge include the following:

- it complements, stimulates and enhances commercial R&D rather than replacing it (Nelson and Rosenberg, 1994);
- it provides new conceptual frameworks and new approaches to problems as well as new data and conclusions about specific issues;
- although it is possible to trace the path from scientific discovery to many leading practical applications, the applications of new knowledge are largely unpredictable (OTA, 1986); and
- there is a need for interaction to convey the tacit knowledge necessary for using published information.

While firms frequently cite publications as an important means of learning about research, they indicate that such publications rarely contain information that is of direct use in innovation (Arundel *et al.*, 1995; Dasgupta and David, 1994). Firms therefore seem to be using these publications as a means of detecting sources of expertise (tacit knowledge), as well as the information itself (codified knowledge). Firms also seem to be publishing to signal their expertise (Hicks, 1995).

These features heavily suggest the importance of strong interactions between those who add to and understand the stock of knowledge, and those who apply it. This is necessary to allow research users to sift the rapidly growing stock of knowledge for relevance to their needs (without themselves knowing the entire stock). Vitally, the process of interaction is also essential for passing on the expertise necessary for the effective use of codified knowledge (Faulkner and Senker, 1995).

Training Skilled Graduates

Many studies of the economic benefits of publicly funded research identify skilled graduates as the primary benefit that flows to firms (Gibbons and Johnston, 1974; Martin and Irvine, 1981). New graduates entering industry bring not only knowledge of recent scientific research, but also abilities to solve complex problems, perform research and develop ideas. Instrumentation skills and techniques are especially valuable.

Nelson (1987) noted that academics often teach what industrial actors need to know even when they do not engage in 'relevant' research for industry. For example, basic research techniques help young scientists to learn to participate in the industrial activities within the firm. As Senker (1995) points out, graduates bring to industry an 'attitude of the mind' and a 'tacit ability' to acquire and use knowledge in new and powerful ways.

Recent graduates bring enthusiasm and a critical approach that can stimulate others and raise standards. Moreover, the skills acquired during education are often a necessary precursor to the development of more specific skills. Even in applied areas of science and engineering, however, the transfer of students into industry is rarely a smooth process. Firms often have to make large investments in training new graduates before they can draw upon their resources to expand the firm's technological competencies. This again underlines the need for commercial investment in their research capabilities and capacity.

New Instrumentation and Methodologies

The challenges involved in research continually force researchers to design new equipment, laboratory techniques and analytical methods to tackle specific research problems. The few attempts that have been made to evaluate the development of new instrumentation and methodologies show that this is an important benefit of public basic research.

Scientific instruments have become almost indistinguishable from industrial capital goods in many industries (Rosenberg, 1992). Examples include semiconductors, electron diffraction, the scanning electron microscope, ion implantation, synchrotron radiation sources, phase-shifted lithography, and superconducting magnets (*ibid.* and OTA, 1995). There are strong linkages between instruments developed in the course of research and those developed by firms (von Hippel, 1988). Innovation surveys show this to be an output from universities that is highly valued by firms (Arundel *et al*., 1995).

Networks and Social Interaction

Government funding for research has a vital role in supporting the development of networks of expertise as it affords individuals and organisations the means to participate in the world-wide community of research and technological development (De Solla Price, 1986).

Although the benefits of such networks are difficult to measure in economic terms, they have been the subject of significant empirical research. Various studies suggest that:
- informal interaction is an important means for firms to learn about publicly funded research;
- good personal relations between firms and public sector scientists are the key to help build the trust and understanding vital for successful collaboration;
- even loose networks can help firms and public researchers identify common goals.

Again, the importance of the tacit dimension of knowledge emerges from this research. Indeed, some analysts go so far as to say that the density of these network interactions is itself a good indicator of the vibrancy of a regional or national innovation system (Cooke and Morgan, 1998).

Technological problem-solving and foreign investment

Publicly funded research and researchers also contribute to the economy by helping industry and others to solve complex problems. Many firms in technologically demanding industries need to combine a variety of technologies in complex ways. Publicly supported research provides an extensive pool of resources from which these firms may draw (Patel and Pavitt, 1995). These pools of resources can help to attract foreign investment. An example is Microsoft's recent decision to locate in Cambridge.

Creation of new firms

Scientific research is often seen as a way of spurring the growth of new firms. Researchers and students can spin out of universities to exploit new ideas and technologies. In the US, the success of Silicon Valley (Stanford) and Route 128 (MIT) in Boston has shown that leading universities can help to stimulate regional and firm growth. In the UK, the growth of new biotechnology firms around Cambridge University also highlights this pattern of development. In a desire to reproduce these experiences, UK universities have moved to promote spin-offs, offering financial and technical support to students and researchers to commercialise their knowledge. The UK government has set a target of increasing university spin-offs by 50 per cent by 2001 (DTI, 1999).

Despite these stories of success and the wave of current expectations, the evidence on the relationship between new firm growth and publicly funded research is mixed. There are several reasons for this mismatch between expectations and evidence:

- university spin-offs have high failure rates;
- academics tend to make poor entrepreneurs and management control is often removed from them before the firm becomes successful;
- there is no one-to-one matching between university research and new firm growth. It is possible to find successful universities within an area with little firm growth.

The provision of social knowledge

Until now the focus of this report has been on technical problem-solving. Yet few problems can be solved by technical approaches alone – technical decisions involve social choices as well. Environmental problems, health care solutions and innovation within firms can all gain from research on the social aspects of technical change.

Many of the benefits that flow from publicly funded natural science and engineering are mirrored in the social sciences. Even apparently 'technical' outputs from natural science such as new instrumentation find equivalents in the social sciences – for example, new economic models. It would be wrong, however, to assume that the social sciences should merely attempt to imitate the natural sciences when it comes to the innovation benefits of research. The social sciences have provided the basis for such public goods as national statistics, censuses, and large parts of the toolbox of the modern management of economies, all of which contribute in fundamental ways to the innovation process. Indeed, the entire way in which society knows about itself is inextricably linked to developments in the social sciences.

The social sciences have recently started to demonstrate a wider potential for making a central contribution to policy for innovation in a 'risk society'. For example:

- research reveals the mutual benefits of innovation and other policies: for instance, support for innovation can greatly improve the variety of options available for addressing environmental problems (Scott *et al*., 1999).
- the social aspects of innovation have become more important in recent years, particularly in the light of ‘risk’ controversies. With issues such as GM food, these have become dominant in the innovation process. Here, the social sciences have begun to offer insights into the closer alignment of business-driven innovation processes with the achievement of other goals such as social inclusion and environmental protection (Scott *et al*., 1999).
- by collecting and reporting information about the public dynamics of risk and innovation, by suggesting how this might be done better in both government and business, and
- by making recommendations for handling risk and uncertainty in ways that are both more scientifically rigorous and more transparent and inclusive (Stirling and Mayer, 1999).

Publicly funded research is, therefore, a vital instrument in reviewing the effectiveness of public policy, for example by providing critical reflections on policy choices. Although sometimes uncomfortable in the short term, such independent scrutiny is likely to be a vital component of the knowledge economy, where the high stakes involved in many policy trajectories mean that internal policy dissent can be curtailed in the interests of short-term efficiency.

Guiding principles for policy

Increase public funding to support the research base

Many leading OECD countries have recognised the importance to the innovation process of public funding for research. In the US, there is a widespread and bi-partisan consensus on the value of increased support for publicly funded research. In 1999, the US Congress agreed to increase support to publicly funded research by five per cent. In the US, support for basic research in 2000 was up 10.4 per cent. The proposed budget of 2001 continues this pattern of support as university-based research will increase by eight per cent (OECD, 2000). In 1999, Germany invested DM1 billion of new money in research. This pattern of investment will continue over the next few years. Canada, Japan, Finland, Denmark and Sweden have also increased their support for research in recent years.

The UK has tried to keep pace with these investment patterns. In the 1998 comprehensive spending review, the UK Government increased its support for publicly funded research, largely through the Joint Infrastructure Fund for university equipment and facilities (DTI, 1998). These funds were essential in ensuring that the UK did not fall further behind in its support for publicly funded research. Yet these increases in support for publicly funded research do not match the contributions made by other OECD countries, such as the US and Germany. The OECD argues that current UK efforts are 'less ambitious' than the first group of OECD countries and that new funding in the UK is 'partly [to] compensate for lower spending over the early part of the 1990s' (OECD, 2000).

The current relatively low level of UK investment in publicly funded research hampers the ability of the UK to participate in the global knowledge-driven economy. The funding gap between the UK and the leaders of the OECD has been growing over the past ten years and only considerable investments will halt this pattern of decline. For example, in 1997 (the most recent year for which figures are available) in order to match US levels of support for higher education R&D, the UK would have had to raise its level of support by 67 per cent in real terms. Even maintaining its position among the lower band of OECD countries will require more investment. For example, to achieve parity with France and Germany, the UK would have to increase spending by 10 per cent in real terms from the 1997 level – and in view of recent increases in investments in their research systems by both France and Germany, this figure will by now be greater.

The impact of the investment gap between the UK and US and other leading OECD countries has not yet appeared in measures of the productivity of the UK research base. Yet, as we have suggested, this may reflect past investment in that current publications produced by the UK research system are the result of past investments. In the current environment of low pay, limited resources, poor morale and casualised labour, the next generation of UK researchers may be less productive than their forebearers.

Students – translating ideas into practice

A key element of government policy should be to encourage and stimulate young people to pursue careers in higher education. University graduates provide a key mechanism for transferring the benefits of public funding to industry. It is vital that government-funded research and student training are conducted in the same institution in order for these benefits to industry to be achieved.

Increasing the student population is not the only issue, however. There are other issues of concern within higher education, such as the continuing under-representation of women in engineering and technology. In addition, a large proportion of foreign students leave the UK after their education, taking the training benefits of their education with them when they go. The data in this report suggest that publicly funded research funding should be increasingly targeted at developing the skills of students, offering them the chance to develop research skills and to apply them to industrial problems. Greater efforts should also be made to encourage women into careers in engineering and technology and to attract foreign students to stay in the UK after their education.

More than paper – expanding beyond publications

Previous studies of the UK research base have tended to focus on its ability to produce academic papers. Publishing is certainly a key indicator of the performance of a research system, but it is a very partial one. Other factors are crucial for the successful translation of research to innovation, such as student training, working with users of research and communicating research findings by less traditional means, including involvement in projects, workshops, on-line publications etc.

The current higher education system provides many incentives for publication, but less significant reward for alternative activities. A new balance between producing publications and other activities of researchers needs to be found. Publications need to be seen in the context of the whole range of activities in which an academic is involved (RAEng, 2000).

Talent, not technology

The UK government has developed policies to encourage the exploitation of knowledge produced by the UK university sector, highlighted in a Competitiveness white paper (DTI, 1998). The strategy includes new funding streams to support technology transfer, including University Challenge (which provides seedcorn funding), Science Enterprise Challenge (which encourages the incorporation of entrepreneurial training into science and engineering curricula) and the HEROBAC scheme (which aims to build capability in knowledge transfer in universities and colleges in in England and Northern Ireland; comparable initiatives to promote commercialisition are under way in Scotland and Wales). The government also set a target of a 50 per cent increase in the number of start-up companies to come out of UK universities (DTI, 1999).

The current approach of the UK government contains much that is positive, but there is also a danger. There are limits to the commercial role of universities and research. Although UK universities could be more entrepreneurial, it is in general true that universities tend to be poor commercial agents. This report suggests that an exaggerated emphasis on promoting university commercialisation would be misplaced because it would see universities as a source of technology rather than talent (Florida, 1999). The UK government needs to be conscious of the limits to commercial exploitation of university research, and should attempt to emulate the best of US practice. Where US universities have been most successful in supporting economic development, they have been allowed the academic freedom to develop and publish new ideas freely and to recruit and retain talented people.

The evidence shows that the transfer of academic ideas into industrial practice is best achieved where universities are given the freedom and resources to conduct high quality research. Short-term, aggressive and narrow drives to force universities to commercialise technology are rarely successful (Geuna, 1999). Universities should be magnets for talented people. The current environment in the UK of low pay, heavy administration and limited flexibility undermines the recruitment and retention of talent in the university sector.

There is a risk that UK universities could face an unattractive prospect: an overly aggressive commercialisation strategy conducted by low paid, disinterested university staff. The prospects for commercialisation of university research will be more successful if UK academics have access to the resources and freedom they need to conduct high quality research and are given the right mix of incentives to promote new ways of working with industry.

Expanding the absorptive capacity of industry

This report provides compelling evidence that, in comparison to other OECD countries, UK industry under-invests in innovation, and especially in research. This has been widely acknowledged in UK government reports (DTI, 1998; DTI, 1999). In many respects, there is little the publicly funded research sector by itself can do to shift this pattern of under-investment. But these patterns of under-investment undermine the ability of the UK research base to contribute to innovation.

Considerable efforts will be required to ensure that the UK does not slip further behind other OECD countries. Recent government efforts to support industry R&D through tax credits are helpful, but further action will be required (DTI, 1998). This action will involve trying to raise the level of commitment of UK firms to innovation and research. The success of the US economy has been, in part, based on the willingness of the US government and industry to fund high levels of quality research. US firms have a strong and sustained demand for new ideas and increasingly use the work of US academics in their innovation processes. Firms in the UK need to learn from this experience and attempt to use the strong UK research base to their advantage.

One possible way to expand the potential for the use of the UK research base is to offer new incentives for foreign-owned companies to base their research activities in the UK. In the past, the quality of the research base in the UK has acted as a magnet for inward investment, but further efforts are required to ensure that the talent of the research base is properly harnessed.

Looking beyond science and technology

We believe that it is necessary to look beyond science and technology to understand the full impact of publicly funded research on innovation. As we have argued, social science and arts and humanities now play an increasingly important role in innovation. Social sciences provide important knowledge about technical and social choices. For example, publicly funded research on management supports the innovative activities of firms in the UK. The rise of creative industries in the UK also indicates that arts and humanities along with other fields such as design and architecture can play a key role in the knowledge-driven economy. Further support for research in arts and humanities, such as the creation of Arts and Humanities Research Council, could help to stimulate these creative industries. In the past, the contribution of these subjects has tended to be ignored in the studies of the role of publicly funded research on innovation. Future studies of the link between publicly funded research and innovation will need to explore the role of these other subjects and their influence on the economy.

More and better evidence

This report has been based on the best available empirical evidence, yet we have found the current evidence to be poor and incomplete. Any investment in researchshould be focused on achieving a better understanding of the innovation process within firms in the UK and of the links between this process and research. Other countries, such as Canada, Australia, and France, have allocated considerable resources to understanding the impact of innovation on their societies. They have on-going research programmes that offer critical, independent and comprehensive evidence on which to base policy. Within the UK, the collection of empirical data is under-developed and this hampers policy-making.

The UK government has recognised this in its white paper on Competitiveness and it has recently published a set of competitiveness indicators (DTI, 1998; DTI, 1999). This new publication is an invaluable source of information on the UK vis-à-vis the rest of the OECD. However, we would suggest that the government needs to go further. The best model for the collection of evidence on innovation comes from Canada and Australia where independent statistical agencies have been set up to conduct and publish surveys and other studies of innovation. For example, Statistics Canada has conducted national surveys on innovation, e-commerce, biotechnology, telecommunications services, R&D in services and innovation in construction (see www.statscan.ca). In the UK, we have only an innovation survey. Statistics Canada is independent of the government, yet publicly controlled. The UK's statistical data collection capabilities are weak by comparison.

References

Aghion, P. and P. Howitt (1995). 'Research and Development in the Growth Process.' Journal of Economic Growth (1): 49-73.

Arthur, W. B. (1983). 'Competing Technologies and Lock In by Historical Events', International Institute for Applied Systems Analysis, Laxenburg, Working Paper.

Arundel, A., G. van de Paal, and L. Soete (1995). Innovation Strategies of Europe's Largest Industrial Firms: Results of the PACE Survey, European Innovation Monitoring System, European Commission, Report N. 23.

Beise, N. and H. Stahl (1999). 'Public research and industrial innovations in Germany.' Research Policy 28: 397-422.

Bush, V. (1945). Science the Endless Frontier, United States Government Printing Office.

Cohen, W. M. and D. A. Levinthal (1989). 'Innovation and Learning: The Two Faces of R & D.' The Economic Journal 99: 569-596.

Cooke, P. and K. Morgan (1998). The Associational Economicy: Firms, Regions, and Innovation. Oxford, Oxford University Press.

Dasgupta, P. and P. David (1994). 'Towards a New Economics of Science.' Research Policy 23: 487-521.

David, P., D. Mowery, and W. E. Steinmueller (1992). 'Analysing the Economic Payoffs from Basic Research.' Economics, Innovation and New Technology 2: 79-30.

David, P. A. (1985). 'Clio and the Economics of QWERTY.' American Economic Review. Papers and Proceedings 75(2): 332-337.

De Solla Price, D. J. (1986). Little Science, Big Science...and Beyond. London
New York, Columbia University Press.

Department of Trade and Industry (DTI) (1998). Our Competitive Future: Building the Knowledge Driven Economy. London, Department of Trade and Industry.

Department of Trade and Industry (DTI) (1999). Our Competitive Future: UK Competitiveness Indicators 1999. London, Department of Trade and Industry.

Dosi, G., C. Freeman, R. Nelson, G. Silverberg, and L. Soete, Eds. (1988). Technical Change and Economic Theory. London, Pinter.

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

Florida, R. (1999). 'The Role of the University: Leveraging Talent, Not Technology.' Issues on Science and Technology Vol.XV(4): 67-73.

Freedland, J. (1998). Bring Home the Revolution. London, Fourth State Paperback.

Freeman, C. and L. Soete (1997). The Economics of Industrial Innovation. London, Pinter.

Geuna, A. (1999). The Economics of Knowledge Production. London, Edwar Elgar.

Gibbons, M. and R. Johnston (1974). 'The role of science in technological innovation.' Research Policy 3: 220-242.

Grossman, G. and E. Helpman (1994). 'Endogenous Innovation in the Theory of Growth.' Journal of Economic Perspectives 8(1): 23-44.

Helpman, E., Ed. (1998). General Purpose Technologies and Economic Growth. Cambridge, Mass. London, The MIT Press.

Hicks, D. (1995). 'Published papers, tacit competencies and corporate management of the public/private character of knowledge.' Industrial and Corporate Change 4: 401-424.

Lundvall, B. A. and S. Borrás (1997). The Globalising Learning Economy: Implications for Innovation Policy, Directorate-General, Science Research and Development, (European Commission).

Mansfield, E. (1991). 'Academic Research and Industrial Innovation.' Research Policy 20: 1-12.

Mansfield, E. (1998). 'Academic Research and Industrial Innovation: an Update of Empirical Findings.' Research Policy 26: 773-776.

Martin, B. R. and J. Irvine (1981). 'Spin-off from Basic Science: The Case of Radio Astronomy.' Physics in Technology 12: 204-212.

Meyer-Krahmer, F. and U. Schmoch (1998). 'Science-based technologies: university-industry interactions in four fields.' Research Policy 27: 835-851.

Narin, F., K. Hamilton, D. Olivastro (1997). 'The increasing linkage between US technology and public science.' Research Policy 26: 317-330.

Nelson, R. (1987). Understanding Technical Change as an Evolutionary Process. Amsterdam, North-Holland.

Nelson, R. (1998). 'The Agenda for Growth Theory: a Different Point of View.' Cambridge Journal of Economics 22(4): 497-520.

Nelson, R. and N. Rosenberg (1994). 'American universities and technical advance in industry.' Research Policy 23: 323-348.

OECD (1992). Technology and the Economy: The Key Relationships. Paris.

OECD (1997). Science, Technology and Industry: Scoreboard of Indicators. Paris, OECD.

OECD (1998). Science, Technology and Industrial Outlook. Paris, OECD.

OECD (1999). Science, Technology and Industrial Scoreboard 1999: Benchmarking Knowledge-based Economies. Paris, OECD.

OECD (2000). Science, Technology and Innovation Policy in OECD Countries - A Review of Recent Developments. Paris, Organisation of Economic Co-operation and Development.

Ostry, S. and R. Nelson (1995). Techno-Nationalism and Techno-Globalism. New York, The Brookings Institution.

Office of Technology Assessment (OTA) (1986). Research Funding as an Investment: Can We Measure the Returns? A Technical Memorandum, Office of Technology Assessment, US Government Printing Office, Washington, DC.

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

Pavitt, K. (1998). 'The Social Shaping of the National Science Base.' Research Policy 27: 793-805.

Romer, P. M. (1986). 'Increasing returns and long-run growth.' Journal of Political Economy 94: 1002-1037.

Romer, P. M. (1994). 'The Origins of Endogenous Growth.' Journal of Economic Perspectives 8(1): 3-22.

Rosenberg, N. (1982). Inside the Black Box: Technology and Economics. Cambridge, Cambridge University Press.

Rosenberg, N. (1990). 'Why Do Firms Do Basic Research (with Their Own Money)?' Research Policy 19: 165-174.

Rosenberg, N. (1992). 'Scientific Instrumentation and University Research.' Research Policy 21: 381-390.

Royal Academy of Engineering (RAEng) (2000). 'Measuring Excellence in Engineering Research.' London, Royal Academy of Engineering.

Saxenian, A. (1994). Regional Advantage: Culture and Competition in Silicon Valley and Route 128. Cambridge, MA, Harvard University Press.

Scott, A., J. Skea, J. Robinson, and E. Shove (1999). Designing Interaction Environmental Research for Wider Social Relevance. Brighton, A Report for the ESRC Global Environmental Change Programme, SPRU.

Senker, J. (1995). 'Tacit Knowledge and Models of Innovation.' Industrial and Corporate Change 4(2): 425-447.

Stirling, A. and S. Mayer (1999). Rethinking Risk. Falmer, East Sussex, SPRU - Genewatch.

Storper, M. (1997). The Regional World: Territorial Development in a Global Economy. New York, The Guilford Press.

Teece, D. (1986). 'Profitting from technological innovation: Implications for integration collaboration, licencing and public policy.' Research Policy 15: 285-305.

Verspagen, B. (1993). Uneven Growth Between Interdependent Economies: an Evolutionary View on Technology Gaps, Trade and Growth. Aldershot, Edward Elgar.

Von Hippel, E. (1988). The Sources of Innovation. New York, Oxford University Press.

Wildavsky, A. (1983). 'Information as an organisational problem.' Journal of Management Studies 20(1): 29-40.

Wolfe, D. (1996). The Emergence of the Region State. The New Knowledge Based Economy. T. Courchene. Toronto: 205-240.