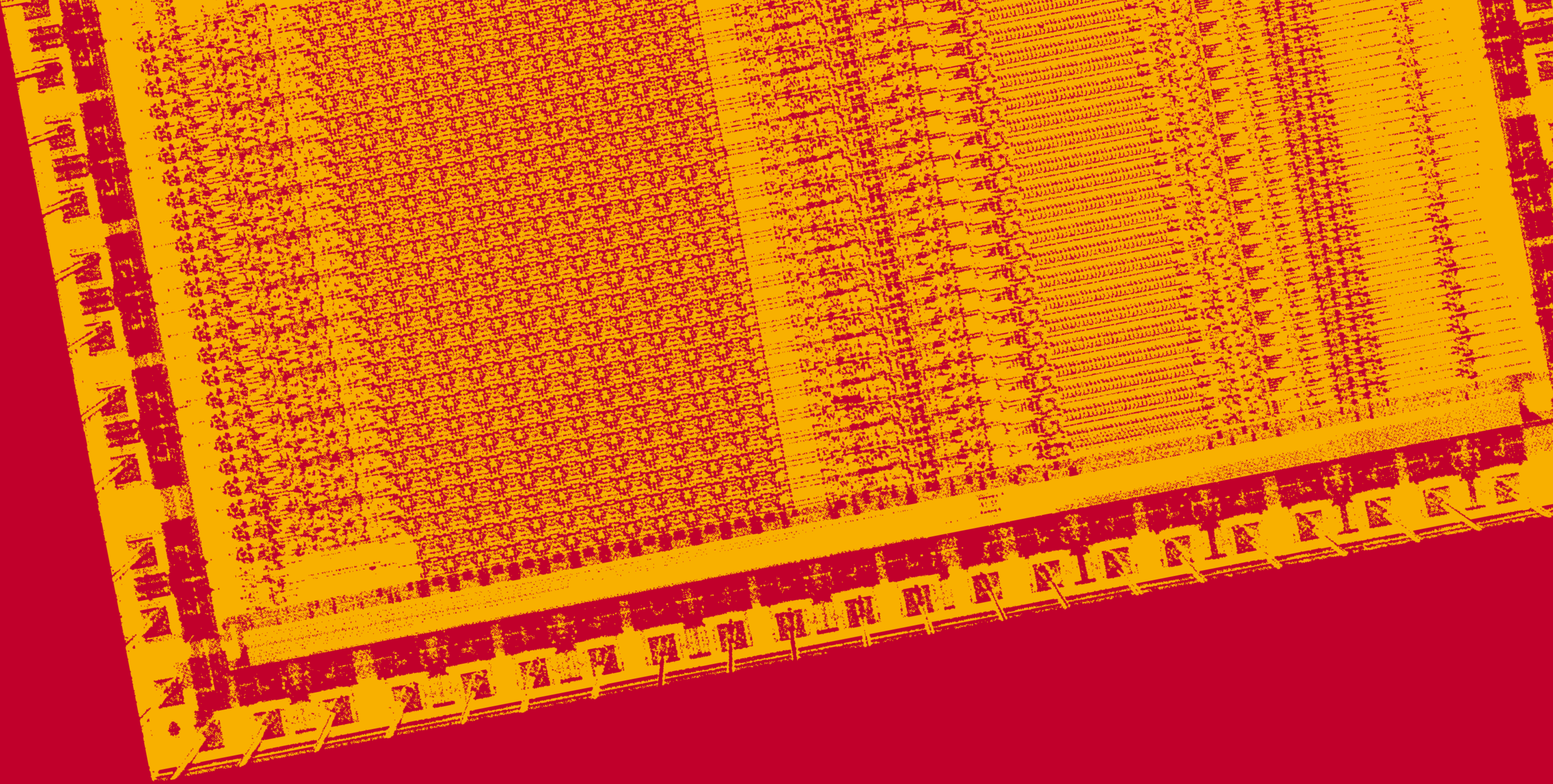

The Scientific Century

securing our future prosperity

CELEBRATE
350 YEARS

THE ROYAL SOCIETY

The Scientific Century: securing our future prosperity

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Cover photo: This is a photograph of the ARM1 silicon chip, designed in 1983-85 by a team at Acorn Computers led by Steve Furber FRS. This is the first ARM processor. ARM chips are now found in over 90% of mobile and personal electronic devices
© Steve Furber, 1985

Contents

Figure from Newton's 'Optiks', Book 1, part 1, Plate II

Executive Summary

No-one can predict the 21st century counterparts of quantum theory, the double helix and the internet. But there is little doubt that advances in science and technology will continue to transform the way we live, create new industries and jobs, and enable us to tackle seemingly intractable social and environmental problems.

Ten years into this new scientific century, the world is slowly recovering from a severe financial crisis. Food security, climate change and health inequalities are rising up international policy agendas. And countries such as China, India and Brazil are reshaping the economic and political landscape.

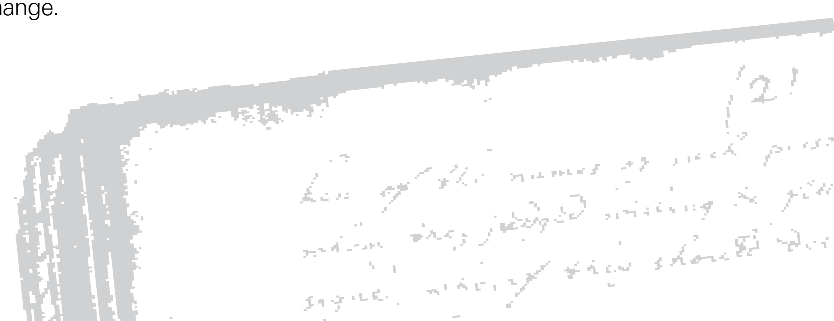
Faced with such uncertainties, the UK must build on its existing strengths. This country has a proud track record of achievement in science and engineering. Today, thanks to sustained investment, we have the most productive research base among the world's leading economies. Our universities are ranked second only to those of the USA. And the outputs of our research are increasingly threaded through the economy.

Over the last 15 years, our universities have responded enthusiastically to the challenge of transferring more of their knowledge into industry, and have given rise to a growing number of high-tech clusters. These developments are still quite fragile and, as was the case in the USA, will need to be nurtured carefully. It would be disastrous if, at this stage, there was a withdrawal of support for our world-class universities, or the incentives which have been put in place to encourage translation, commercialisation and knowledge exchange.

At the same time as we have improved our record on science and innovation, other countries have improved theirs. Our scientific leadership, which has taken decades to build, can quickly be lost. While the UK contemplates further reductions in spending on higher education and research, most other major economies, including the USA, China, France and Germany, have outlined ambitious plans to increase investment and boost their innovation performance.

Drawing on evidence, analysis and extensive consultation across the UK's science, engineering and innovation communities, this report distils two urgent messages. The first is the need to place science and innovation at the heart of the UK's long-term strategy for economic growth. The second is the fierce competitive challenge we face from countries which are investing at a scale and speed that we may struggle to match.

As the Royal Society celebrates its 350th anniversary, we want to provoke a richer debate about the contribution that science and innovation will make to the UK's future. If the right policy choices are made now, the UK can remain at the vanguard of international science and secure its prosperity throughout the scientific century.



Recommendations and actions

Recommendation 1: Put science and innovation at the heart of a strategy for long-term economic growth

- Create a new long-term framework for science and innovation committing to increased expenditure
- Outline spending plans over a fifteen year period (2011-2026)
- Prioritise investment in scientific capital – including infrastructure and skills
- Expand the R&D tax credit

Recommendation 2: Prioritise investment in excellent people

- Direct a greater proportion of Research Council funding to investigator-led research
- Increase the length and quality of UK PhD training
- Support transferable skills training for researchers
- Increase the number of postdoctoral fellowships

Recommendation 3: Strengthen Government's use of science

- Review strategic science spending by Government departments
- Expand the Small Business Research Initiative to support innovative procurement
- Provide Departmental Chief Scientific Advisers with greater resources
- Appoint a Chief Scientific Adviser to HM Treasury

Recommendation 4: Reinforce the UK's position as a hub for global science and innovation

- Extend the geographic reach of the UK Science and Innovation Network
- Increase support for mechanisms, such as the Science Bridges scheme, which link UK research groups with partners overseas
- Incentivise more of the world's best scientists to remain in, or relocate to, the UK
- Improve visa conditions for visiting scientists and researchers to the UK

Recommendation 5: Better align science and innovation with global challenges

- Create strong global challenge research programmes, led by RCUK, to align scientific, commercial and public interests
- Reform research funding and assessment to support and reward interdisciplinary research
- Use public and stakeholder dialogue to help identify and shape these challenges
- Ringfence departmental contributions to priority research areas

Recommendation 6: Revitalise science and mathematics education

- Provide incentives to recruit, retain and attract teachers back to science subjects
- Commit to increasing the numbers of primary teachers with science expertise
- Establish new expert groups to advise on the development of science and mathematics curricula and qualifications

Record of the founding of the Royal Society and first meeting on 28 Nov 1660 © The Royal Society

The Advisory Group

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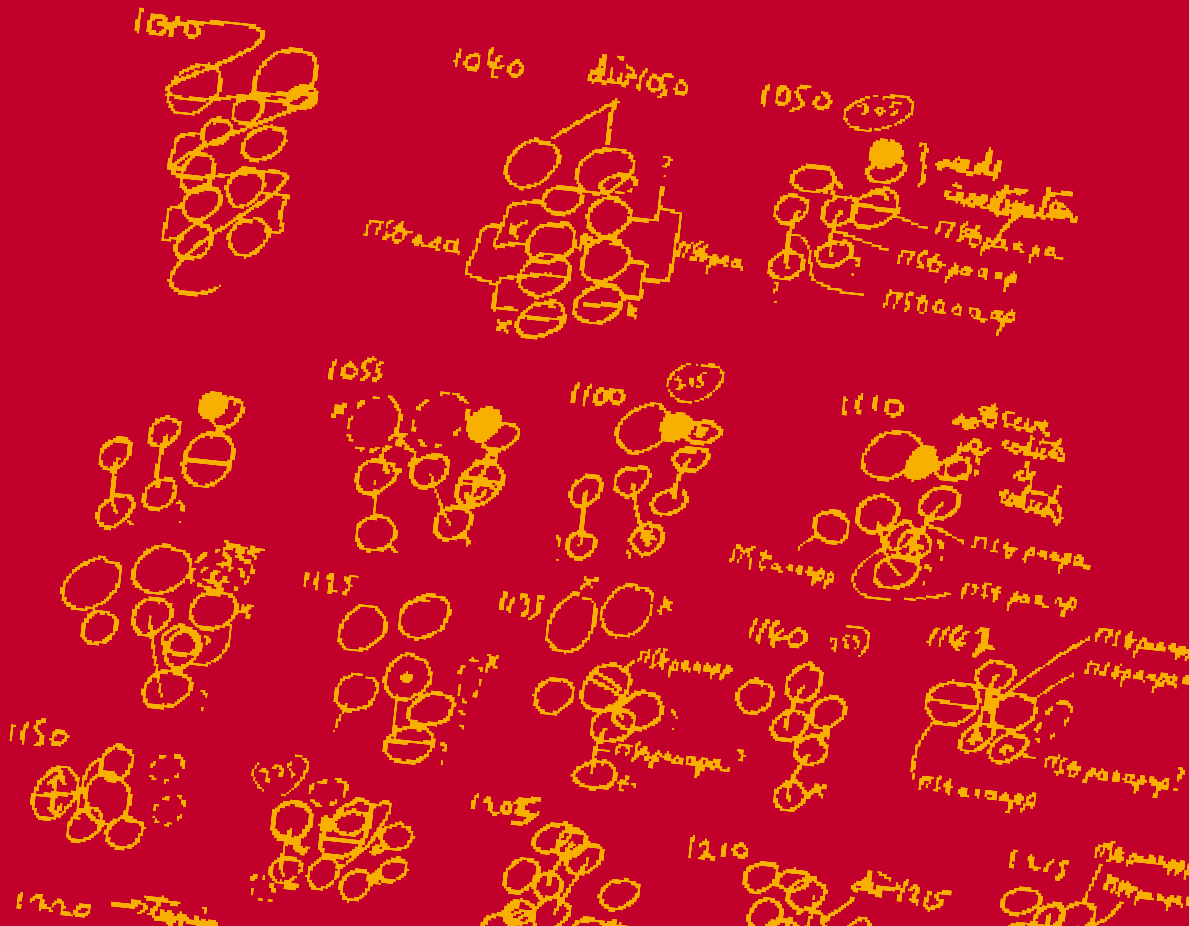
PART 1

The fruits of curiosity



This sketch of cell division of *Caenorhabditis elegans*, the nematode worm, comes from Sir John Sulston FRS, the 2002 Nobel Prize Laureate in Physiology or Medicine. Sulston and colleagues detailed the development of *C.elegans* from egg to adult, eventually determining the fate of each and every cell of an organism. © John Sulston, 1980

PART 1

The fruits of curiosity

On a damp spring morning in 1993, John Sulston watched from the window of his makeshift office in Hinxton as a large muddy hole was being dug in the field outside. The foundations were soon laid for what would become one of Europe's leading centres for biomedical research: the Wellcome Trust Sanger Institute. By March 1994, 130 people were working there, using state-of-the-art equipment to map, sequence and analyse genomes. Thanks to their contributions, the genome of the yeast *Saccharomyces cerevisiae*, with 12 million bases, was published in 1996, and that of the nematode *Caenorhabditis elegans* in 1998. But the Sanger Institute is most celebrated for its contribution to the Human Genome Project, a collaborative effort by scientists in seven countries. A full draft was completed in April 2003, with the Sanger Institute responsible for around one third of the total.

When the Sanger Institute was first established, Sulston recalls how 'the very notion of sequencing the human genome was regarded by many biologists as foolish and wasteful of resources'. Such attitudes quickly changed. The Human Genome Project was heralded by some as the start of a 'century of biology', following the domination of the 20th century by physics and the 19th century by chemistry. Sulston is more modest, pointing out that, 'This is only the beginning. For all the fuss about sequencing the human genome, the total process of understanding is much harder and is open ended.' But as genomic science advances, it is likely to transform healthcare, creating new approaches to the diagnosis, prevention and treatment of many common diseases.[1]

Observations on duckweed.
Antoni Van Leeuwenhoek to
The Royal Society, 25 December 1702.
© The Royal Society

This will not only be a century of biology. It will be a century of mathematics, chemistry, physics and engineering too,[2] a century in which advances at the frontiers of multiple disciplines will transform the way we live, create new industries and jobs, and enable us to tackle seemingly intractable social and environmental problems.

We cannot predict this century's counterparts of quantum theory, the double helix and the computer – nor where the next generation of innovators will be trained and inspired. But one thing seems certain: unless we get smarter, we'll get poorer. The UK's relative economic standing will sink unless more scientific breakthroughs take place and are exploited here in the UK.

These are the opportunities of this scientific century, and the focus of this report. Drawing on evidence, analysis, case studies and extensive consultation across the UK's science and engineering communities, the report distils two urgent messages. The first is that science and innovation must remain the basis of any long-term strategy for growth. The second is the fierce competitive challenge we face from those countries which are now investing in research at a scale and speed that we may struggle to match.

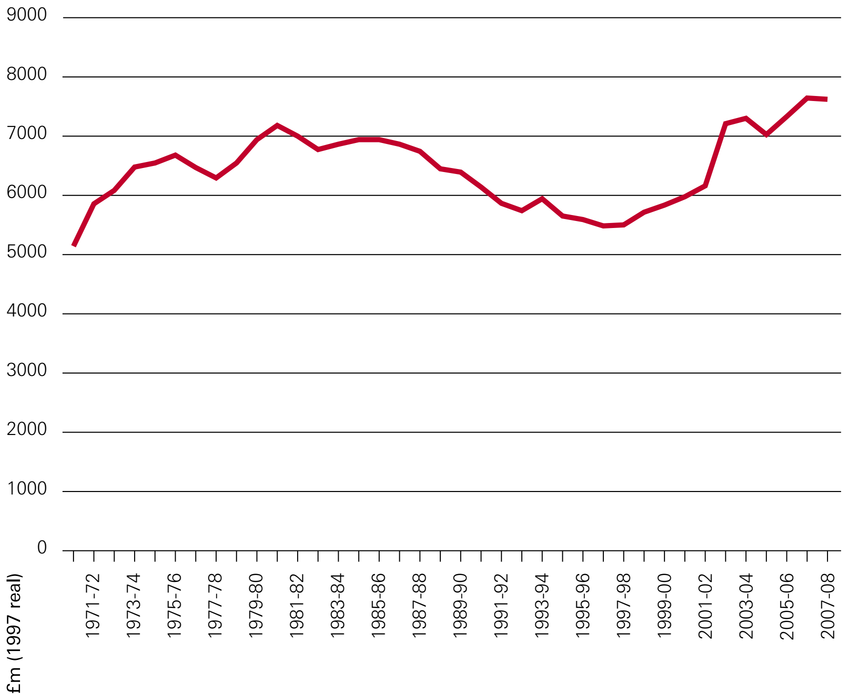
The UK has great scientific strengths, which underpin our society, culture and economy: we must build on these and continue to aspire to be the best country in the world in which to do science. Despite the financial pressures that now confront us, we must not let short-term choices undermine the progress that has been achieved. As the Royal Society celebrates its 350th anniversary, we want to provoke a wider debate about how science and innovation can underpin our prosperity for the next decade and beyond.

Investing for growth

Over the last few decades, countries have risen and fallen, research fields have waxed and waned, but British science has adapted and sustained its reputation for excellence.[3] Recent investment has reversed the relative decline of UK science that occurred in the 1980s (see Figure 1.1).[4] The UK produces more publications and citations per pound spent on research than any other G8 nation. With 1% of the world's population, the UK produces 7.9% of the world's publications, receives 11.8% of citations, and 14.4% of citations with the highest impact (see Figure 1.2[6]). Earlier generations worried about a brain drain from the UK.[7] We are now a net importer of scientists and innovators, and these people are more highly-skilled than ever before.[8]

The success of the UK research base has been supported by effective policies to generate more value from this increased investment, in particular through the Technology Strategy Board (TSB). There has been a remarkable growth in the amount of universities' knowledge exchange. Between 2000 and 2008, the number of patents granted to universities rose by 136% and consultancy income increased by 222%.[9] In 2007/08, university spin-out companies employed nearly 14,000 people and had

Figure 1.1 **Public R&D expenditure, 1970-2008**[5]



1 House of Lords Science and Technology Committee (2009). *Genomic Medicine*. The Stationery Office: London, UK; Academy of Medical Sciences (2010). *Reaping the rewards: a vision for UK medical science*, Academy of Medical Sciences: London, UK.

2 In many places throughout this report, we use the term 'science' as shorthand for disciplines in the natural sciences, technology, engineering and mathematics.

3 Weinberg B (2009). *An assessment of British science over the twentieth century.* Economic Journal **119**, 538, F252–F269.

4 Martin B (1994). *British science in the 1980s—has the relative decline continued?* Scientometrics **29**, 1, 27–56; Lord Sainsbury of Turville (2007). *The Race to the Top: A Review of Government's Science and Innovation Policies.* Stationery Office: London, UK.

5 Sources of statistics: BIS (2009). *SET Statistics. Science, Engineering and Technology Indicators.* Department for Business, Innovation and Skills: London, UK; and Office for National Statistics. Public R & D expenditure includes Government departments, Research Councils, universities and nationalised industries.

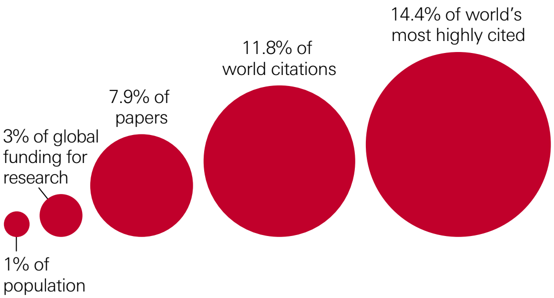
6 Evidence Ltd (2009). *International comparative performance of the UK research base.* Department for Business, Innovation and Skills: London, UK; OECD (2009). *Main Science and Technology Indicators* (MSTI): 2009 Edition. Organisation for Economic Coorporation and Development: Paris, France; *Science and Engineering Indicators 2010.* National Science Foundation: Arlington, VA, USA.

7 Royal Society (1963). *Emigration of scientists from the United Kingdom: Report of a committee appointed by the Council of the Royal Society.* Royal Society: London, UK.

8 Findlay A (2001). *From Brain Exchange to Brain Gain: Policy Implications for the UK of Recent Trends in Skilled Migration from Developing Countries.* International Migration Papers **43**. International Labour Office: Geneva, Switzerland.

9 Source: HEFCE (2008). *Higher Education – Business Community Interaction survey 2008.* Higher Education Funding Council for England: Swindon, UK.

Figure 1.2 **The UK's share of global science**



a combined turnover of over £1.1 billion.[10] Over the past decade, university bioscience departments alone have generated over 200 spin-out companies.[11] The UK now has an emerging network of centres of excellence for technologies and industrial innovation.[12]

Science is one area where the UK has strengthened its competitive advantage. But this advantage can easily be lost. Continued investment is necessary to increase productivity in high value-added sectors, as part of the ongoing transition to a knowledge economy (see Figure 1.3).[13] Alongside high-tech manufacturing in sectors such as pharmaceuticals, aerospace, software and industrial design, UK services are increasingly knowledge-intensive, and now account for three quarters of gross value added (GVA) and over 80% of employment in the UK.[15] In the wake of the global financial crisis, as policymakers seek a more diverse, balanced and sustainable economy, science and innovation will be more important than ever before.[16]

Rising expenditure on UK scientific research, primarily through universities and the Research Councils, has produced clear benefits. One often-overlooked change has been to scientific infrastructure, which had been allowed to erode during the 1980s and early 1990s. Since 1998, the Joint Infrastructure Fund, the Large Facilities Capital Fund and the Science Research Infrastructure Fund have ploughed more than £3 billion into repairing and replacing ageing laboratories. In return for increased investment, the Treasury's Ten Year Framework for Science and Innovation, produced in 2004, set out the need for 'greater responsiveness of the research base to the economy'.[17]

In the mid-1990s, policy makers looked to Silicon Valley with envy. It seemed to have everything in place: world class universities with surrounding 'clusters' of high-technology companies and spin-outs supported by a buoyant venture capital market.[18] Fifteen years later, the UK has developed its own high-tech clusters, most notably in Cambridge, but also around the universities of Manchester, Oxford, Southampton, Surrey and York.

In his 2007 review, former science minister Lord Sainsbury described science and innovation as an ecosystem.[19] The health of the whole system depends on the health of its constituent parts and, crucially, on the relationships between them. The Sainsbury Review found that there had been a step change in the knowledge transfer system, with the performance of leading British universities now close to that of their top American counterparts.

As the policies of the last two decades start to yield real results, there is a need to take a long-term view of future challenges to the UK's global leadership in science and innovation. This is particularly urgent at a time when many more countries are investing heavily in research.

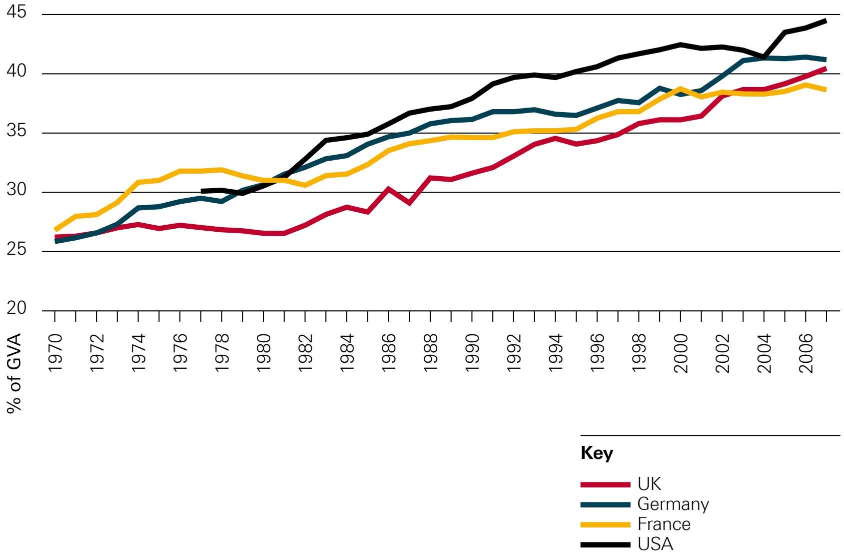
The value of science

Science and innovation policies for the 21st century must start with a clear rationale, looking carefully at the benefits that flow from continued investment in research. Science is primarily motivated by curiosity – a desire to learn more about the world.[20] The accumulation of new knowledge is recognised as a public good in and of itself, but science proceeds in the understanding that this curiosity bears fruits which are of wider economic and social benefit.

Economic history reveals the central role of science and innovation in the productivity growth of industrialised nations.[21] However, what can seem clear with hindsight is hazier for policy makers looking to the future. The economic benefits of science are often long-term (see Case study 1.4) and there are many ways in which publicly-funded science has an impact on the economy (see Figure 1.5).

Of the types of impact shown in Figure 1.5, the first and second (increasing useful knowledge and creating new firms) receive the greatest attention from policy makers, who often assume a neat linear model in which innovation follows from science, with the benefits captured rapidly, in the same country as the research takes place.

Figure 1.3 **Knowledge-intensive services and high-tech manufacturing as percentage gross value added (GVA), 1970-2007**[14]



10 BIS, HEFCE, Scottish Funding Council, HEFCW and Department for Employment and Learning (2008). *Higher Education – Business and Community Interaction Survey 2007-2008.*

11 BBSRC (2009). *Economic Impact Baseline 2009 Update.* BBSRC: Swindon, UK.

12 HM Government (2010). *Going for Growth: Our Future Prosperity.* Department for Business, Innovation and Skills: London, UK.

13 This is formally rooted in the economics of Endogenous Growth Theory, which builds on the ideas of Robert Solow, who included technological innovation in growth equations for the first time. See: Solow R (1956). *A contribution to the theory of economic growth.* Quarterly Journal of Economics **70**, 1, pp 65–94; Porter M & Ketels C (2003). *UK Competitiveness: Moving to the Next Stage.* DTI Economics Paper no 3, Department of Trade and Industry: London, UK, and Economic and Social Research Council: Swindon, UK.

14 This graph shows knowledge-intensive services and high-tech manufacturing value-added as a share of gross value added. Source: European Union (2009). *EU KLEMS Growth and Productivity Accounts.* European Union: Brussels, Belgium.

15 Royal Society (2009). *Hidden Wealth: The Contribution of Science to Service Sector Innovation.* Royal Society: London, UK.

16 HM Government (2010). *Going for Growth: Our Future Prosperity.* Department for Business, Innovation and Skills: London, UK; NESTA (2009). *The Innovation Index: Measuring the UK's investment in innovation and its effects*, National Endowment for Science, Technology and the Arts: London, UK.

17 HM Treasury/ Department for Trade and Industry/ Department for Education and Skills (2004). *Science and Innovation Investment Framework 2004–2014* (pp10–11). HM Treasury: London, UK.

18 'Clustering' was promoted as a convenient means to marry the desire for quality scientific research with the desire to create high-growth companies. See: DTI (1999). *Biotechnology Clusters. Report of a Team Led by Lord Sainsbury, Minister for Science.* Department for Trade and Industry; DETR (2000). *Planning For Clusters.* Department of Environment, Transport and Regions; HM Treasury (2006). *Barker Review of Land Use Planning, Final Report – Recommendations.* Stationery Office: London, UK.

19 Lord Sainsbury of Turville (2007). *The Race to the Top: A Review of Government's Science and Innovation Policies.* Stationery Office: London, UK.

20 Nowotny H (2008). *Insatiable curiosity: Innovation in a Fragile Future.* MIT press: Cambridge, MA, USA.

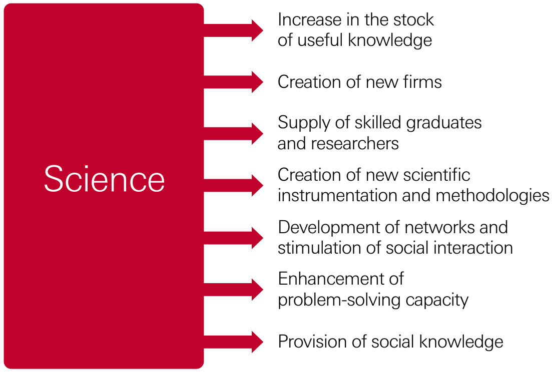
21 Landes D (1969). *The Unbound Prometheus: Technological Changes and Industrial Development in Western Europe, 1750 to the Present.* Cambridge University Press: Cambridge, UK; Mokyr J (1990). *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford University Press: Oxford, UK; Lipsey R, Carlaw K & Bekar C (2006). *Economic Transformations: General Purpose Technologies and Long-Term Economic Growth.* Oxford University Press: Oxford, UK.

Case study 1.4
From Faraday to the iPod

Michael Faraday was a leading light of 19th century science. He began his career as secretary to Sir Humphry Davy, himself a formidable chemist and inventor. Faraday then joined the Royal Institution, where his experiments allowed him to elucidate the principles of electromagnetism and build the first dynamo. Explaining a discovery to then Chancellor of the Exchequer William Gladstone, Faraday was asked, 'But after all, what use is it?' He famously, but perhaps apocryphally, replied, 'Why sir, there is every probability you will be able to tax it'.

Faraday's ideas were taken forward by James Clerk Maxwell, Lord Kelvin and numerous others, including Albert Fert and Peter Grünberg. Fert and Grünberg received the 2007 Nobel Prize in Physics for work on giant magnetoresistance, showing that tiny changes in magnetism can generate large changes in electrical resistance. Their 1988 discovery revolutionised the way that computers store information. The minuscule hard drives inside laptops and the earliest iPods would have been impossible without Faraday's pioneering work more than 150 years earlier.

Figure 1.5 **How science has an impact**[22]



There are numerous problems with looking at innovation in this way. Scientific knowledge is collective, public and international. It can be difficult to pinpoint which aspects of research have contributed to particular innovations. There are often time lags between basic research and its applications.[23] Retreating to the comforts of the linear model by focusing on the most visible and immediate impacts of science may obscure the hidden value produced over a longer term.

A 2008 report from the Medical Research Council, Wellcome Trust and the Academy of Medical Sciences concludes that, even in medicine, where research is often highly-targeted, the lag between research and health benefits can be anywhere from 10 to 25 years.[24] Close-to-market technologies also require a lengthy gestation. The development of new biotechnology processes takes, on average, three and a half years from initial design to commercialisation, while microelectronics products require well over five years.[25]

Recent policies have placed great emphasis on the economic impacts of research.[26] This is understandable, given the scale of public investment and the economic challenges facing the UK. But targets and metrics cannot guarantee impact and, if implemented crudely, may prove counterproductive. Economic impacts are also only one dimension of the wider public value of science. Excellent research has by definition a significant impact, much of which is on the research field concerned. Other impacts are also likely to be significant, but are often impossible to predict in advance.[27] Debates over impact within the research community have become unnecessarily polarised, and are in danger of diverting attention from the many benefits that research brings to the economy, society and public policy. Recent clarification from the Higher Education Funding Council for England (HEFCE)[28] and the Research Councils about their approach to impact[29] has been helpful and should go some distance to addressing the concerns voiced by sections of the research community.

Alongside increasing knowledge and creating firms, the other channels through which science has an impact (see Figure 1.5) are no less important. Much of the value of science derives from scientists themselves: their skills and expertise, and the way that they move through the economy, are just as important as the knowledge that they leave behind.[30]

Scientific people

Science requires investment, infrastructure and an enabling policy environment, but its most important resource is people. Policy needs to be more closely attuned to the life cycle of scientists' careers, from school to retirement, and to the contribution of those who are trained in science but choose to work in other sectors.[31]

Young people need improved science education, whether they are destined to become professional scientists or scientifically-literate citizens. As with

Sketches from paper 'Pulsars – Basic Problems', April 1982 © The Royal Society

22 Martin B and Tang P (2007). *The benefits from publicly funded research.* SPRU working paper 161. Science and Technology Policy Unit, University of Sussex.

23 *Ibid.*

24 These lags are offered for the particular case of cardiovascular disease research. See: Health Economics Research Group (HERG), Brunel University, Office of Health Economics (OHE) and RAND Europe (2008). *Medical research, what's it worth?* Report For the Medical Research Council, the Wellcome Trust and the Academy of Medical Sciences.

25 Lord Sainsbury of Turville (2007). *The Race to the Top: a Review of Government's Science and Innovation Policies*, Table 6.2. Stationery Office: London, UK.

26 Research Council Economic Impact Group (2006). *Increasing the Economic Impact of Research Councils. Advice to the Director General of Science and Innovation.*

27 Royal Society (2009). *Response to HEFCE's second consultation on the assessment and funding of higher education research.* Royal Society: London, UK.

28 HEFCE (2009). *Research Excellence Framework: Second consultation on the assessment and funding of research.* Higher Education Funding Council for England: Bristol, UK.

29 Thorpe A (2009). *Impact is created in immeasurable ways 2*. Letter to Times Higher Education. 12 November 2009; House of Commons Science and Technology Committee (2010). *The impact of spending cuts on science and scientific research* Minutes of Evidence on 3 February 2010. Available online at www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/uc335-i/uc33502.htm

30 Salter A *et al.* (2000). *Talent, Not Technology: Publicly Funded Research and Innovation in the UK.* Science and Technology Policy Research Unit, University of Sussex.

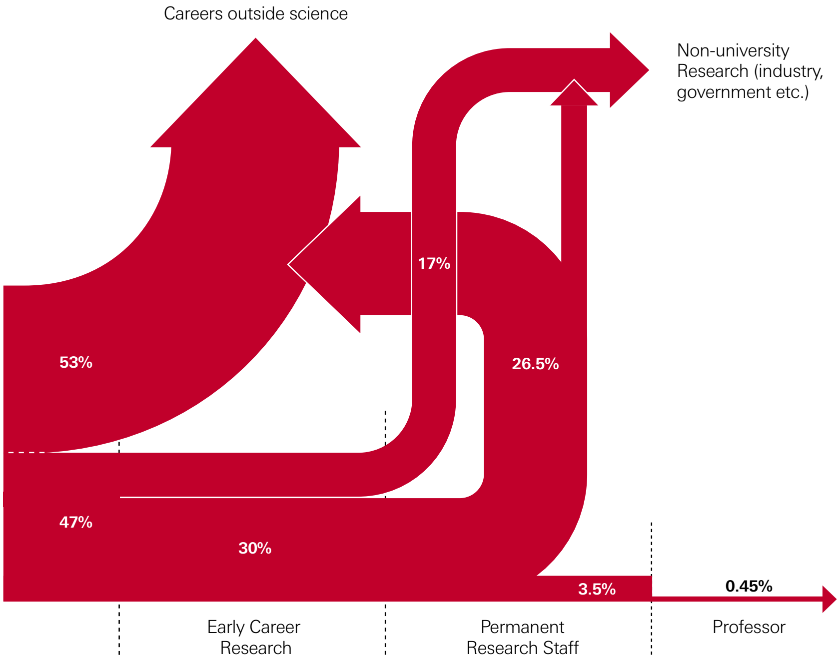
31 Royal Society (2009). *Hidden Wealth: The Contribution of Science to Service Sector Innovation.* Royal Society: London, UK.

other areas of education, science and mathematics have suffered from rapidly-changing political expectations and reforms. Scientific subjects demand the input of subject specialists for the development of their curricula and modes of assessment. The number one priority must be the quality of these specialist teachers. Prior to 2009, the UK had failed to meet its recruitment targets for secondary science and mathematics teachers every year for over a decade. The training, recruitment and retention of primary science and mathematics teachers are a source of particular concern. The Royal Society's own research suggests that without excellent teachers there is little hope of inspiring children to stick with science.[32]

A PhD can be a gateway to a scientific career. But the majority of people undertaking a PhD will end up in careers outside scientific research (see Figure 1.6). The journey from PhD student to professor is punctuated by key transition points. At each of these points, some scientists leave scientific careers, and only a tiny proportion of PhD students can expect to end up as university professors. Policy can help ensure job security and flexibility, so that the best scientists can reasonably expect long, rewarding careers.

Despite progress in the past decade, ensuring a diverse scientific workforce remains a challenge. Women are still under-represented in the latter stages of scientific careers, particularly in the physical sciences. While 35% of all researchers in science-related disciplines are women, the proportion falls to 30% for lecturers, 21% for senior lecturers and just 11% for professors.[36] Since 2004, the Government has funded a dedicated centre to support women entering, returning to and progressing in scientific careers, but science is still seen by many as a highly demanding career that is incompatible with family life.[37]

Figure 1.6 **Careers in and outside science**



This diagram illustrates the transition points in typical academic scientific careers following a PhD and shows the flow of scientifically-trained people into other sectors. It is a simplified snapshot based on recent data from HEFCE[33], the Research Base Funders Forum[34] and from the Higher Education Statistics Agency's (HESA) annual Destinations of Leavers from Higher Education' (DLHE) survey. It also draws on Vitae's analysis of the DLHE survey[35]. It does not show career breaks or moves back into academic science from other sectors.

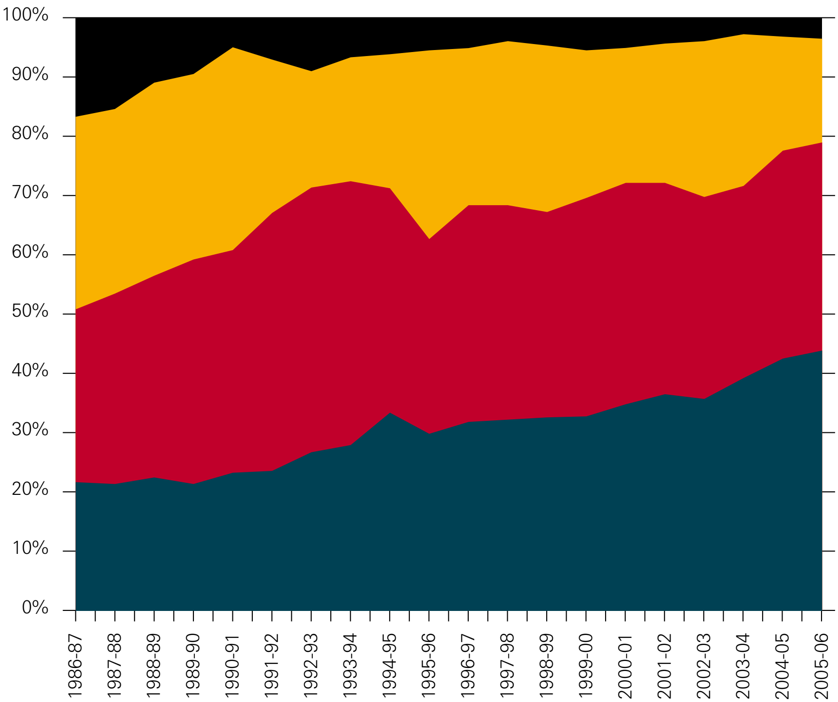
The diversity of science

Science is often discussed as though it is one process or one set of institutions and people. (We are no doubt guilty of over-simplifying in this report.) Even within a single scientific discipline, scientists bring a breadth of expertise, interests and motivations. Some will be driven by the pursuit of knowledge; others by a desire to make an impact on people's lives; many will be motivated by both aims and others besides.

Scientific research is often subdivided according to whether it is 'basic' or 'applied', 'blue-skies' or 'strategic'. Such distinctions can be helpful when thinking about how we fund and evaluate research. Despite some concerns that the balance of public science funding is shifting in an applied direction, data shows that over 20 years it has in fact shifted towards basic research (see Figure 1.7).

However, there is a danger in over-emphasising such differences. As the Council for Science and Technology argues in a recent report, we need a richer language for 'the complex, reflexive relationship between research (of all types) and impacts, whether social or economic'.[39] Scientists themselves can be guilty of defending their own patch of basic or applied research at the expense of a broader debate about the system as a whole.

Figure 1.7 **Types of publicly-funded science**[38]



Key

- Experimental development
- Applied – specific
- Applied – strategic
- Basic

32 Royal Society (2004). *Taking a Leading Role—Scientists Survey.* Royal Society: London, UK.

33 HEFCE (2005). *Staff employed at HEFCE funded HEIs. Trends, profiles and projections.* Higher Education Funding Council for England: Swindon, UK.

34 Research Base Funders Forum (2008). *First Annual Report on Research Staff Covering the Period 2003/04 to 2006/07.* Department for Innovation, Universities and Skills: London, UK.

35 Vitae (2009). *What Do Researchers Do? First Destinations of Doctoral Graduates by Subject.* Vitae: Cambridge, UK.

36 HESA (2009). *Resources of Higher Education Institutions 2007/08.* Higher Education Statistics Agency: Cheltenham, UK.

37 See: www.ukrc4setwomen.org; Royal Society (2009). *Mothers in Science. 64 Ways to Have It All.* Royal Society: London, UK.

38 Department for Business, Innovation and Skills (2009). *SET Statistics. Science, Engineering and Technology Indicators.* This uses 'Frascati' definitions, where 'basic research' is carried out for the advancement of knowledge; 'strategic applied research' has practical aims, but no specific uses; 'specific applied research' is aimed at particular products, processes or systems; and 'experimental development' uses existing knowledge to develop and test new technologies or processes.

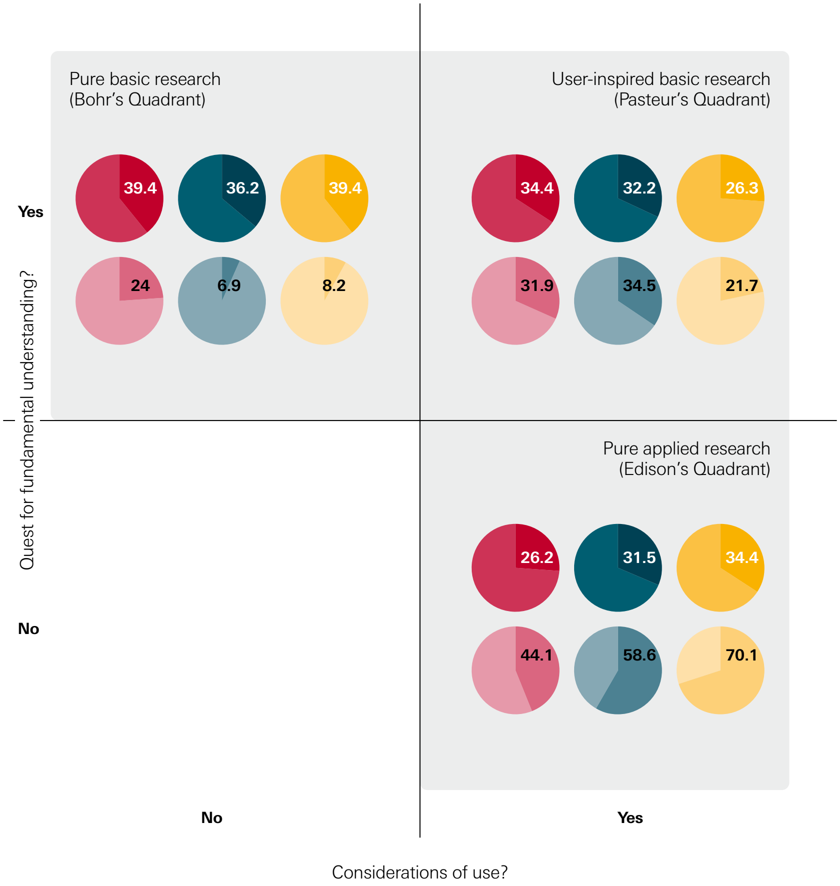
39 CST (2010). *A Vision for UK research.* Council for Science and Technology: London, UK.

PART 1

The fruits of curiosity

Basic science is often labelled 'curiosity-driven'. But all research is fundamentally motivated by curiosity. Different sorts of science are interdependent and equally important. We must not lose sight of the ways in which they reinforce one another.

Figure 1.8 **How UK academics classify their own work**[42]



Key
- Physics, Mathematics
- Biology, Chemistry, Veterinary science
- Social sciences
- Arts and Humanities
- Engineering, Materials science
- Health sciences

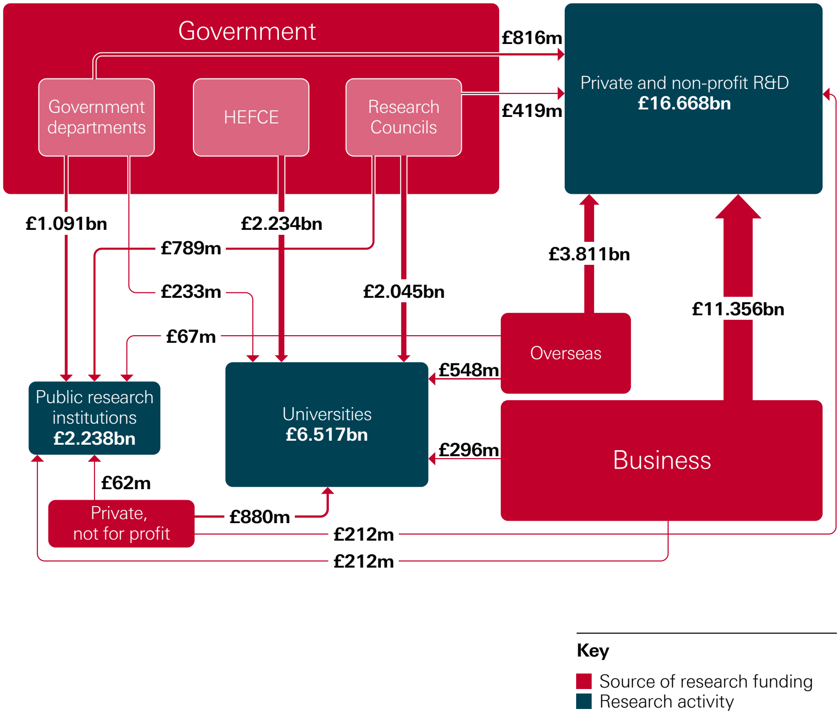
Donald Stokes describes the large body of scientific activity that is driven by a desire for both scientific understanding and social benefit. He calls this 'Pasteur's Quadrant', which he contrasts with the fundamental research of scientists like Niels Bohr or the purely applied research of Thomas Edison.[40] Of basic research funded by Research Councils in 2006/7, 60% fits into Pasteur's Quadrant.[41] This emphasis is also reflected in the results of a 2009 UK Innovation Research Centre survey of 22,000 academics – although results vary by discipline (see Figure 1.8).

Who funds UK science?

The money that flows from Government to the Research Councils is only one of many investment streams in UK science. Increased funding has meant that UK academic science has grown markedly, but it is easy to forget that most science is still conducted outside universities (see Figure 1.9). Businesses conduct two thirds of research and development (R&D), a quarter takes place in universities and government and charity research make up the remainder. British charities such as the Wellcome Trust, Cancer Research UK and the Gatsby Foundation and international players like the Gates Foundation support more than a billion pounds worth of research in universities and research institutes.[43] These non-governmental investments in science are crucial, and their value is recognised through policies such as the R&D tax credit and the Charity Research Support Fund. But they also depend on substantial public investment.

It has been wrongly claimed in the past that public spending on science might 'crowd out' private sector investment. The evidence suggests the opposite. Multiple flows of funding reinforce one another and bind the science base together (see Figure 1.9). There is a strong correlation between overall levels of university and business R&D investment.[45] In those sectors of the UK economy where companies spend substantially on R&D, such as pharmaceuticals and aerospace, corporate investment is underpinned by public spending on research.

Figure 1.9 **Flows of funding in UK science**[44]



40 Stokes D (1997). *Pasteur's Quadrant. Basic Science and Technological Innovation.* Brookings Institution Press: Washington, DC, USA. According to Stokes, the fourth quadrant is not empty (it might include particular sorts of data collection) but it can certainly be considered less important.

41 BIS (2009). *SET Statistics. Science, Engineering and Technology Indicators*, taking orientated-basic research as a proxy for Pasteur's Quadrant.

42 Data from: Abreu M, Grinevich V, Hughes A, Kitson M (2009). *Knowledge Exchange between Academics and the Business, Public and Third Sectors.* UK-Innovation Research Centre. See p 62/Exhibit A2—Stokes's Quadrants by discipline.

43 Evidence provided by the Association of Medical Research Charities. Total research spending of all the charities under the AMRC umbrella was £965,524,608 in 2008/09.

44 This diagram disaggregates familiar statistics on science budgets in order to represent different funding streams in public, private and charity science. Source: Department for Business, Innovation and Skills series, *Science, Engineering and Technology statistics*, release date November 2009. All figures are for 2007, and are estimates derived from National Statistics surveys of government and business R&D expenditure, adjusted with reference to National Statistics *First Release Gross Domestic Expenditure on Research and Development 2007* (March 2008). Gross expenditure on R&D is classified using OECD definitions, so estimates may differ from other accounts. Figures shown exclude expenditure by UK businesses on overseas R&D (£1.95bn) and universities' own expenditure on research (£308m). 'Public research institutions' includes government research laboratories and Research Council laboratories.

45 Falk M (2006). *What drives business research and development intensity across OECD countries?* Applied Economics **38**.

Case Study 1.10 **Monoclonal Antibodies: From the lab to the clinic**

In 1975, César Milstein and Georges Köhler isolated and reproduced the monoclonal antibodies that defend our bodies against foreign invaders. This technique was developed to improve our understanding of the process of antibody diversification. But when they received their Nobel Prize in 1984, Milstein said: 'it was up to us to demonstrate that the exploitation of our newly-acquired ability to produce monoclonal antibodies 'à la carte' was of more importance than our original purpose.' Work to this end has helped further our understanding of basic cell biology, as well as diseases such as cancer and heart disease.

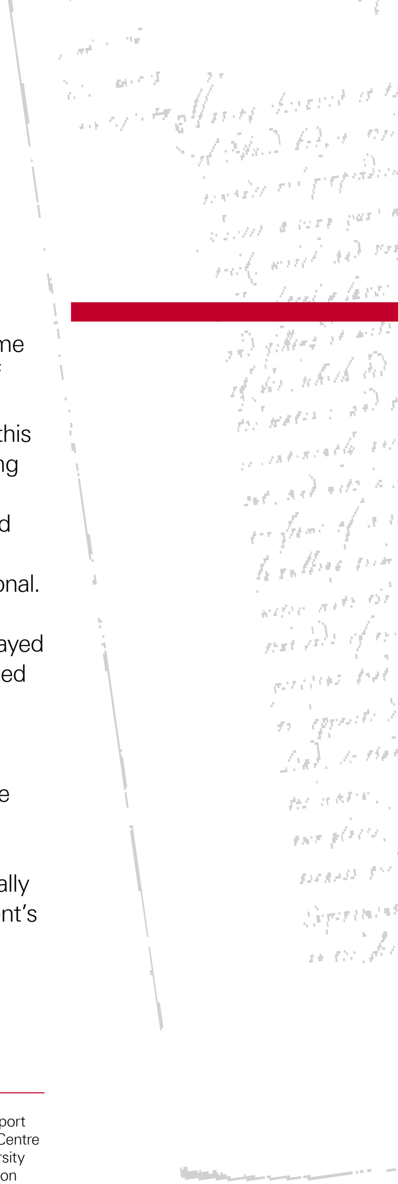
The drive to turn this knowledge into treatment had to overcome several hurdles. Monoclonal antibody technology was developed by immunising mice. This produced rodent antibodies that were initially rejected by humans.

In 1986, Greg Winter, working alongside Milstein at Cambridge's MRC Laboratory of Molecular Biology, developed a technique to 'humanise' mouse monoclonal antibodies by genetic engineering, removing the final barrier to their development as novel therapeutic drugs. Winter later developed another genetic engineering technique to make human antibodies in bacteria, bypassing the need to immunize mice or humans.

Monoclonal antibodies now account for a third of all new pharmaceutical treatments. Sufferers of breast cancer, arthritis, asthma and leukemia are already benefiting from new drugs and dozens more are in late-stage clinical trials. According to the Biotechnology and Biological Sciences Research Council (BBSRC), the market for monoclonal antibody drugs is now worth an estimated US$32 billion.[46]

UK companies developing antibody technology have been a start-up success story. Winter's pioneering technologies have been licensed to around 50 companies, and generated over £300 million in royalties for the MRC. Winter's work has also provided the science underpinning Cambridge Antibody Technology (founded by Winter and Dr David Chiswell, and acquired by AstraZeneca in 2006 for £702 million), and Domantis, founded by Winter and Dr Ian Tomlinson (and acquired by GlaxoSmithKline in 2006 for £230 million). Winter says 'I was lucky; the MRC allowed me the freedom to roam with my scientific research over the borders to medicine and industry'.

Penicillin graph, c.1940



Robert Hooke's sketch
on refraction of ice, 1662

How can we increase the value of science?

The innovation ecosystem consists of numerous people and institutions, with different (and sometimes conflicting) motives. The stewardship of this system demands close attention to detail. There is a growing recognition that, rather than focusing on the public funding within its control, government needs to improve the quality of interactions across the entire system. Universities are becoming much more innovative. But as academic researchers transform the way that they engage with business, it has become clear that some problems persist elsewhere within the innovation ecosystem.[47]

University-industry collaboration

The best universities interact with companies globally and locally. In the most information-intensive parts of the economy, we can detect a 'death of distance',[48] but in other sectors, geography still matters (see Case study 1.10). Evidence shows that companies, especially foreign companies, choose to site their R&D labs near the best universities.[49] High-tech firms typically migrate in packs, exchanging knowledge face-to-face and drawing on local expertise and skills.[50]

Following the 2003 Lambert review,[51] consistent efforts by government to increase the value of university research to wider society have paid some dividends. UK universities are now more aware of business needs than at perhaps any time in their history. However, evidence is also emerging that this change in attitudes can be pushed too far, straining delicate relationships.[52]

Knowledge exchange is too often misconceived as a one-way process of knowledge transfer. Innovation is in reality more open and multidirectional. Companies attach great importance to informal knowledge exchange, and this is typically underplayed in policies.[53] Incentives for engaging with users need to be pitched at the level of individual academics, and need not be exclusively financial.[54]

Policies that bring together companies and universities, formally and informally, need sensitive and sustained support. In service sectors, there are some indications that collaborations between businesses and the public research base are actually declining.[55] The Advanced Institute of Management's survey of Engineering and Physical Sciences Research Council (EPSRC) collaborations found a growing proportion of firms reporting barriers to collaboration between 2004 and 2008.[56]

46 BBSRC (2009). *Science making an economic difference*. Available online at www.bbsrc.ac.uk/science/impact/economic-impacts.aspx

47 Lord Sainsbury of Turville (2007). *The Race to the Top: A Review of Government's Science and Innovation Policies.* Stationery Office: London, UK.

48 Griffith R, Lee S, van Reenan J (2007). *Is distance dying at last? Falling home bias in fixed effects models of patent citations.* National Bureau of Economic Research working paper no 13338.

49 Abramovsky L, Harrison R, Simpson H (2007). *University research and the location of business R&D.* Economic Journal **117**, 519.

50 Jaffe A (1989). *Real effects of academic research.* American Economic Review **79**, 5; Audretsch D & Feldman M (1996). *R&D spillovers and the geography of innovation and production.* American Economic Review **86**, 4; Audretsch D (1998). *Agglomeration and the location of innovative activity.* Oxford Review of Economic Policy **14**, 2.

51 HM Treasury (2003). *Lambert Review of Business—University Collaboration. Final Report.* Stationery Office: London, UK.

52 Bruneel J, d'Este P, Neely A, Salter A (2009). *The Search for Talent and Technology: Examining the Attitudes of EPSRC Industrial Collaborators Towards Universities.* Advanced Institute of Management Research: London, UK.

53 Abreu M, Grinevich V, Hughes A, Kitson M, Ternouth P (2008). *Universities, Business and Knowledge Exchange.* Council for Industry and Higher Education: London, UK, and Centre for Business Research: Cambridge, UK.

54 PACEC (2009). *Evaluation of the effectiveness and role of HEFCE/OSI Third Stream Funding: culture change and embedding capacity in the Higher Education sector toward greater economic impact.* A report to HEFCE by PACEC and the Centre for Business Research, University of Cambridge. Higher Education Funding Council for England: Bristol, UK.

55 2005 and 2007 UK Innovation Surveys; also Robson S & Haigh G (2007). *First findings from the UK Innovation Survey 2007.* Economic & Labour Market Review **2**, 4.

56 See Bruneel J, d'Este P, Neely A, Salter A (2009). *The Search for Talent and Technology: Examining the Attitudes of EPSRC Industrial Collaborators Towards Universities.* Advanced Institute of Management Research: London, UK.

PART 1

The fruits of curiosity

Case study 1.11 **Open innovation at Pfizer in Sandwich**

Pfizer's base in Sandwich, Kent is an unlikely location for Europe's largest research and development facility. It is nearer to France than it is to a big UK city.

Once a manufacturing facility, the US company has created a site that now feels like a major research university. The growth of Sandwich rests upon the quality of science in the UK. The pharmaceutical industry needs a queue of medicines in its pipeline. Research resources are squeezed into one end and products emerge from the other. Across the industry, however, anxiety is growing that the pipeline is leaking. Blockbuster drugs like Viagra, created in Sandwich, are becoming far rarer.

As a result, companies like Pfizer are now starting to open up their innovation processes, by drawing in new institutions, partners and scientific disciplines. Pfizer's R&D is now likely to bring chemists together with biologists, mathematical modellers, clinicians and computer scientists. They may be based anywhere in the world, and they need not work for Pfizer. In the last ten years, Pfizer UK has published research with more than 300 external bodies, including universities, charities and other companies. Almost a quarter of its research has been published in collaboration with the US and another quarter with European partners.

This 'open innovation' model poses challenges for big companies, not least in the skills they demand of their workforce. In addition to deep expertise, researchers need the ability to make connections to disciplines alongside their areas of deep expertise. They also need to be able to engage with a growing 'ecosystem' of scientists and organisations across the globe working in industry, academia and clinical practice.

The recent discovery and development of Maraviroc exemplifies this approach. Maraviroc is an anti-retroviral medicine and is the first of a new class of anti-HIV drugs. Developed in Sandwich and launched in 2007, its origins can be traced back to the discovery of HIV coreceptors by academic scientists in 1996. Pfizer started to investigate, with the help of a small biotech company, both a new drug and a diagnostic to identify the sub-group of patients who would benefit. Some of this research is happening at Sandwich, but much of it is underway in hospitals and universities around the world.

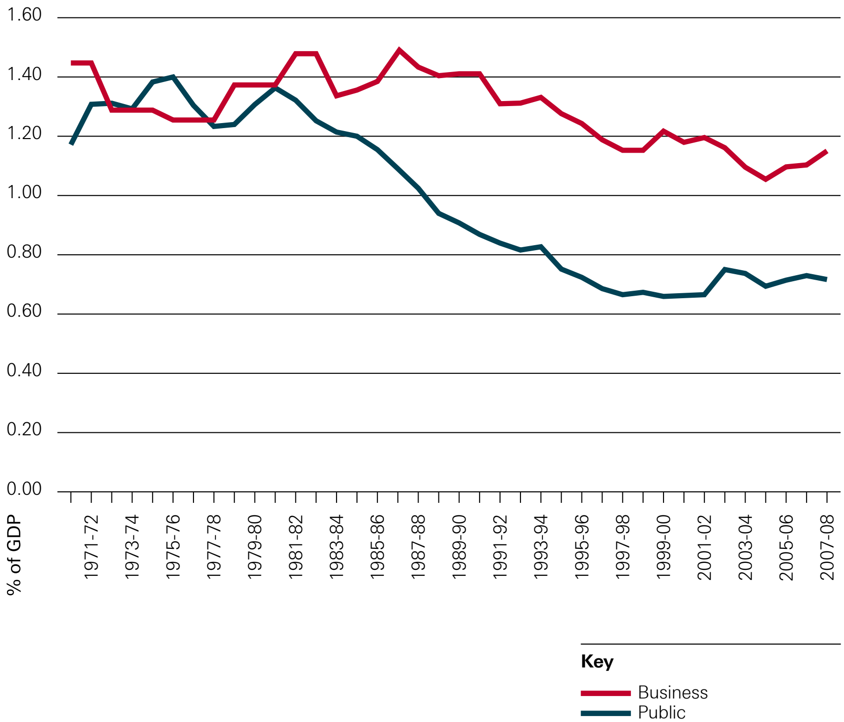
Figure from Newton's 'Optiks', Book 1, part 1, Plate II © The Royal Society

Strengthening business innovation

In the pharmaceuticals, aerospace and oil and gas sectors, the UK is home to R&D facilities for some of the world's largest companies (see Case study 1.11). However, despite the contribution of companies like GlaxoSmithKline, AstraZeneca, Royal Dutch Shell and Rolls-Royce, business R&D expenditure across the board remains a weakness in the UK's innovation system. In 2005 US companies spent 1.9% of GDP on R&D and German companies 1.8%, while British companies spent just 1.2% (see Figure 1.12).[57] In the 1980s, the R&D gap between the UK and the USA was mostly due to low public sector R&D. By the 1990s, low levels of business spending became a more significant problem,[59] particularly among small and medium-sized enterprises, which in 2005 accounted for just 3.3% of UK business R&D expenditure.[60]

The UK's comparatively low level of business R&D is in part due to its economic structure, following a thirty year transition from a manufacturing-led economy to one dominated by the services sector. Services businesses benefit greatly from science and technology, but generally spend less on formal R&D than their manufacturing counterparts.[61] However, structural differences cannot completely account for the UK's position: the USA has a similar services-led economy but spends a greater proportion of its national income on R&D.[62]

Figure 1.12 **R&D expenditures as share of gross domestic product (GDP), 1970-2008**[58]



57 Abramovsky L, Griffith R, Harrison R (2005). *Background facts and comments on 'Supporting growth in innovation: enhancing the R&D tax credit'.* Institute for Fiscal Studies Briefing Note 68. Institute for Fiscal Studies: London, UK.

58 Source: Office for National Statistics: Newport, UK.

59 Griffiths R & Harrison R (2003). *Understanding the UK's poor technological performance.* Institute for Fiscal Studies Briefing Note 37. Institute for Fiscal Studies: London, UK.

60 Hughes A (2010). *Entrepreneurship and Innovation Policy: Retrospect and Prospect*, in Uberoi V et al. (eds.) (2010). *Options for Britain: Cross—cutting Policy Issues.* Wiley-Blackwell: Chichester, UK.

61 Royal Society (2009). *Hidden Wealth: The Contribution of Science to Service Sector Innovation.* Royal Society: London, UK.

62 Abramovsky L, Griffith R, Harrison R (2005). *Background facts and comments on 'Supporting growth in innovation: enhancing the R&D tax credit'.* Institute for Fiscal Studies Briefing Note 68. Institute for Fiscal Studies: London, UK.

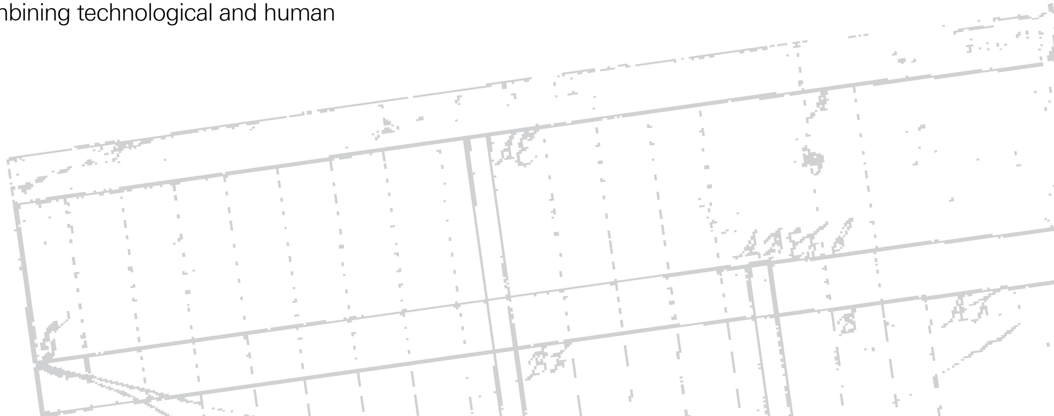
Attempts to support private sector spending through the R&D tax credit have met with some success. UK R&D is highly internationalised, making its location sensitive to tax changes introduced elsewhere in the world. Competitive tax credits are therefore an important enabler of a healthy innovation ecosystem. The challenge now is to encourage greater uptake of the R&D tax credit by smaller firms.

The management of innovation

Where industrial companies once maintained their own large research laboratories – Bell Labs and Xerox PARC are among the best known – they are now more likely to look outwards, to customers, other companies and universities for new ideas.[63] As corporate innovation becomes more networked, the quality of interactions with university partners becomes more important and the management of knowledge becomes more complicated.[64] Open innovation does not remove the need for in-house R&D. If a company is to appropriate external ideas, it still needs R&D skills. Firms with strong internal R&D have greater 'absorptive capacity'. They are better able to recognise the value of external information and apply it to their own innovation processes.[65]

One influential study of manufacturing companies found that the primary defining feature of innovative firms was their ability to share personal or tacit knowledge.[66] Combining technological and human resources to drive innovation demands sophisticated organisational design and management.[67] Too many UK firms remain poorly equipped to manage such processes.[68] UK firms spend less than a third of their German counterparts on developing their managers, and UK managers are less likely than other professionals to receive formal training and accreditation.[69]

Access to finance is another barrier to innovation.[70] Corporate venturing, angel investing and sector specialist venture capital can be crucial in bridging the gap between university research and wealth creation. Funding for university spin-out companies can accelerate the commercialisation of excellent science (see Case study 1.13). The UK private equity sector has grown over the last decade, rising from £3 billion worth of deals in 2003 to £12 billion by 2007,[71] second only to the US. But this expansion has not helped enough new businesses.[72] The real value of funds flowing into high-tech early-stage firms has fallen from £622 million in 2000 to £124 million in 2008 (although this fall in part reflects the dot-com boom, and subsequent crash, at the start of the decade).[73] Recent interventions by Government have led to a sharp increase in the number of deals with public-sector backing. But the problem is more complex than a simple 'equity gap',[74] and efforts to improve the flow of venture capital in the UK need to go beyond publicly-backed funds.



Figures from Brouncker's paper on the compression of air under water, 1671
© The Royal Society

Case study 1.13 **Plastic Logic: a fertile relationship between science and engineering**

The 'Cambridge Phenomenon' has seen four decades of growth in the number of high-tech companies emerging from and around Cambridge University. Even within this crowded field, Plastic Logic stands out. It is built on what its co-founder (and member of this report's advisory group) Richard Friend describes as 'a fertile relationship, where the science guides engineering and the engineering feeds back into the science'.

In the mid-1980s, Friend was a relatively junior physicist at Cambridge University's Cavendish Laboratory, trying to understand the movement of electrons in carbon-based semiconductors. He and colleagues made a diode using a semiconducting polymer. They found it emitted light when driven electrically. Almost by accident, they had made a plastic LED. 'The inspiration to study the semiconducting properties of molecules came from curiosity, but was rapidly paralleled by the desire to make something from it,' says Friend. But there were still years of basic research needed to achieve the depth of knowledge required for a technological breakthrough.

Further opportunities for commercialisation – of printed polymer transistor circuits – emerged in 2000. Friend, now Cavendish Professor of Physics, and his colleague Henning Sirringhaus formed Plastic Logic. Support came from the entrepreneur Hermann Hauser, who has fostered links between Cambridge scientists and businesses for almost three decades. Plastic Logic's most recent innovation is the 'Que', an A4 plastic sheet displaying electronic newspapers, books and magazines, which is lighter and easier to read than its rivals.

63 Chesbrough H (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology.* Harvard Business School Press: Boston, MA, USA.

64 Glückler J (2007). *Economic geography and the evolution of networks*. Journal of Economic Geography **7**, 5, pp 619–634.

65 Cohen W & Levinthal D (1990). *Absorptive capacity: a new perspective on learning and innovation.* Administrative Science Quarterly **35**, pp 128–152.

66 Nonaka I & Takeuchi H (1995). *The Knowledge Creating Company.* Oxford University Press: Oxford, UK.

67 Enne E & Richter A (2009). *The whole is more than the sum of its parts—or is it? A review of the empirical literature on complementarities in organisations.* European Business School Research Paper Series 09-07.

68 Porter M & Ketels C (2003). *UK competitiveness: moving to the next stage.* DTI Economics Paper no 3. Department of Trade and Industry: London, UK, and Economic and Social Research Council: Swindon, UK.

69 Mabey C & Ramirez M (2004). *Developing Managers: A European Perspective.* Chartered Institute of Management: Northamptonshire, UK.

70 Robson S & Haigh G (2007). *First findings from the UK Innovation Survey 2007.* Economic & Labour Market Review **2**, 4.

71 BVCA/PriceWaterhouseCooopers (2009). *Private Equity and Report on Investment Activity 2008.* British Venture Capital Association: London, UK.

72 Perriakis Y & Mason C (2008). *Shifting Sands: The Changing Nature of the Early-Stage Venture Capital Market in the UK* (p 9). National Endowment for Science, Technology and the Arts: London, UK.

73 Figures from British Venture Capital Association: London, UK, expressed in 2008 prices.

74 NESTA/BVCA (2009). *From Funding Gaps to Thin Markets: An Evaluation of Government-Backed Venture Capital Schemes* (p 20). NESTA: London, UK.

21st century science and innovation policy

The curiosity of scientists is limitless, but public funds to support research are not. Choices have to be made about what to fund and how. These choices are complicated by the time cycles involved; research yields dividends over decades, and cannot be made to dance to the rhythm of public spending rounds. The space required for curiosity-driven research needs to be protected by policy makers.[75]

Scientific knowledge moves freely, and the impacts of research are often felt far from where it originally occurred. The linear model of basic research through to innovation bears little relation to reality.[76] Instead, innovation is often distributed and collaborative, blending external needs with technological possibilities (see Case study 1.16).

Newton's diagram taken from a Letter from Newton to Oldenberg, 6 June 1672, that discusses the doctrine of light and colour.
© The Royal Society

Case Study 1.16 **ARM: connecting world class science with worldwide markets**

In 2006, Sir Robin Saxby announced his retirement as chairman of ARM Ltd, ending a relationship that gave birth to one of the great British technology success stories of recent times: the first billion-dollar company to come out of the Cambridge area.

ARM was founded in 1990, as a spin-out from Acorn Computers called Advanced RISC Machines. Today, the company is a leader in designing the intricate software systems on microprocessors embedded in electronic devices. Their designs are used in more than 95% of the world's mobile phones, and are widespread in the netbook and e-reader markets as well.

Part of ARM's success came from the cutting edge engineering that was taking place in and around Cambridge in the late 1980s. And part came from Saxby's injection of business acumen, acquired through working at firms like Motorola. He developed a business model that allowed the engineers to concentrate on chip design, while others manufactured the products. ARM sells innovation, taking a cut from every product that includes its intellectual property.

ARM's early chips had fewer than 30,000 transistors. Chips now hold millions, and they are measured in nanometres. The competition is fierce, but ARM has been able to stay at the cutting edge of chip design by linking the best available science, from Cambridge and elsewhere, to an explosive global growth in demand.

The significance that the linear model still occupies in the imagination of policy makers is one example of how historical assumptions, and the retelling of familiar myths, continue to shape contemporary science and innovation policy. These assumptions can blind us to more sophisticated approaches. As the historian David Edgerton argues, rather than constructing policy on the basis of 'Haldane principles and linear models', we should instead 'Think *about* them and their significance in debates, and how they support each other... note how they limit discussion to particular parts of a much more complex whole.'[77]

In the same way, narrow accounts of the impact or value that science creates for our society can act as an impediment to good policy making. The economic contribution of science – vital and significant though it is – should not eclipse its wider social, public and cultural value.[78] Alongside measurements of quantity and scale (levels of investment, numbers of publications, flows of PhD students), 21st century science policy needs to become more adept at addressing questions of quality, purpose and direction.[79] It should resist the temptation to treat scientific and technological progress as homogenous or one-directional, and instead support a 'more balanced and diverse portfolio of trajectories'.[80]

Discussion of these trajectories should also be opened up to a wider circle of participants.[81] Surveys show that public appreciation of the benefits of science remains high. Most people trust scientists, but they also appreciate that scientific research can raise social and ethical questions that merit wider debate.[82] The public increasingly expect to become more involved in decisions involving science, and the UK has been a pioneer in processes of public dialogue and engagement.[83] The Royal Society has contributed to this, by encouraging debates about developments at the frontiers of science, such as nanotechnology[84] and geoengineering.[85]

These efforts can improve the robustness of policy, but they can also strengthen science. The UK's open approach to public debate about stem cell research has encouraged its development, relative to other countries.[86] And the streams that connect science and democracy run deeper: 'The very virtues that make democracy work are also those that make science work: a commitment to reason and transparency, an openness to critical

75 Nowotny H (2009). *Insatiable Curiosity: Innovation in a Fragile Future.* MIT Press: Cambridge, USA.

76 NESTA (2008). *Total Innovation: Why harnessing the hidden innovation in high-technology sectors is crucial to retaining the UK's innovation edge.* National Endowment for Science, Technology and the Arts: London, UK.

77 Edgerton D (2009). *The 'Haldane Principle' and other invented traditions in science policy.* History and Policy. Available online at: www.historyandpolicy.org/papers/policy-paper-88.html.

78 Wilsdon J, Wynne B and Stilgoe J (2005). *The Public Value of Science.* Demos: London, UK.

79 ISEI (2008). *Who owns Science? The Manchester manifesto.* Institute for Science, Ethics and Innovation, University of Manchester: Manchester, UK.

80 Stirling A (2007). *A General Framework for Analysing Diversity in Science, Technology and Society.* Journal of the Royal Society Interface, **4** (15), pp 707-719, August 2007.

81 House of Lords Science and Technology Committee (2000). *Science and Society, Third report.* The Stationary Office: London, UK.

82 RCUK and DIUS (2008). *Public Attitudes to Science 2008, a Survey.* Research Councils UK: Swindon, and Department for Innovation, Universities and Skills: London, UK.

83 DIUS (2008). *Innovation Nation: Background Analysis: Strengths and Weaknesses of the UK Innovation System.* Department for Innovation, Universities and Skills: London, UK.

84 Royal Society (2004). *Nanoscience and nanotechnologies: opportunities and uncertainties.* Royal Society: London, UK.

85 Royal Society (2009). *Geoengineering the climate: science governance and uncertainty.* Royal Society: London, UK.

86 Nowotny H and Testa G (2009). *Die Gläsernen Gene. Gesellschaftliche Optionen im molekularen Zeitalter.* Edition Unseld, Suhrkamp: Frankfurt, Germany.

scrutiny, a scepticism toward claims that too neatly support reigning values, a willingness to listen to countervailing opinions, a readiness to admit uncertainty and ignorance.'[87]

The context for policy is also changing. As the next part of this report describes, science and innovation are inherently and increasingly international. Yet most policies are set at the national level, and weighted towards strengthening competitive advantage, rather than enabling cross-boundary collaboration.

The UK is well-placed to benefit from a more global, networked science and innovation system. But our leadership is far from assured. Speaking recently about the prospect of cuts in the UK research budget, Ralph Cicerone, President of the US National Academy of Sciences, offered a sober warning: 'You might not see anything immediately, but you will begin to see a movement of scientists over time. They will go to where the opportunities are – to the US and to places like Singapore that have invested heavily in science.'[88]

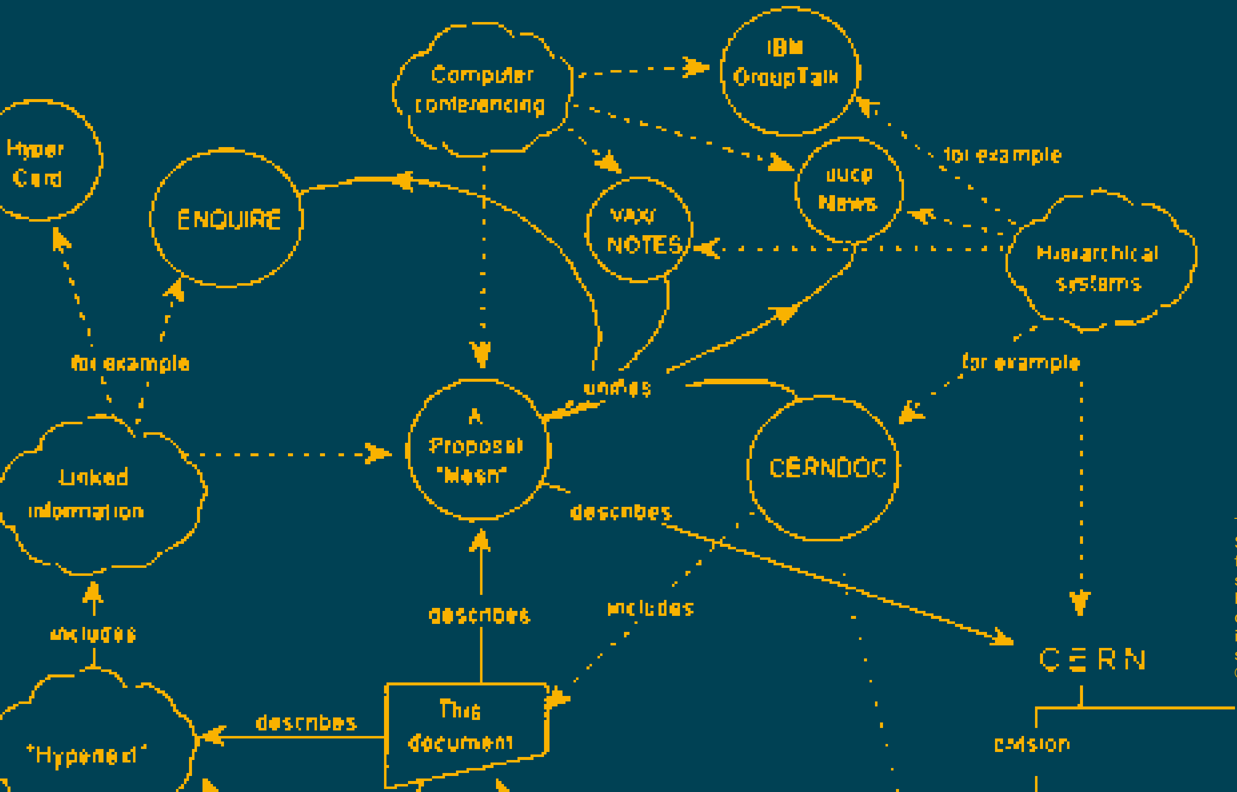
Engraving by J Basire showing the construction of "Specula of six-feet aperture..." by William Parsons, Earl of Rosse, from Philosophical Transactions, Volume 151, 1861, Plate 24, p 681
© The Royal Society

87 Jasanoff S (2009). *The Essential Parallel between Science and Democracy.* Seed Magazine, 17 February 2009.

88 Remarks at the AAAS Annual Meeting, San Diego, February 2010 (reported in Henderson M (2010). *We'll take your talent, warns US scientists.* The Times, 23 February 2010).

PART 2

New frontiers of science



This schematic was drawn by Sir Tim Berners-Lee FRS in his proposal for an information management system at CERN. Described as ‘vague, but exciting’ by his supervisor, the distributed hypertext system described in the proposal eventually became the structure behind the World Wide Web.

PART 2

New frontiers of science

At the 1908 Olympic Games in London, China failed even to field a team. Eighty years later, in Seoul, it finished in 11th place. In Athens, in 2004, it climbed to second, just behind the United States. And in 2008, as Beijing played host to the most spectacular Olympics in history, China topped the table for the first time, with a tally of 51 gold, 21 silver and 28 bronze medals.

This sporting success is emblematic of a wider shift in the economic and political order, which has seen a more confident China gradually assume a prominent role on the world stage. But if this is what China can achieve in sport, how quickly will it become a leader in science and technology? In both areas, the Chinese government has set ambitious, long-term targets and mobilised vast resources to achieve them. Just as the $40 billion spent on the Beijing Games dwarfed anything that had gone before, so China is now at an early stage in the most ambitious programme of research investment the world has ever seen. Since 1999, China's spending on R&D has increased by almost 20 percent each year, and it is now the world's second largest R&D investor after the US.[1] In 2006, the Chinese government approved a new fifteen-year plan for science and technology.[2] Meeting its targets will require investment in 2020 to be six times what it was in 2005.

These investments are starting to yield impressive results. Since 1981, the number of peer reviewed papers produced by China has increased 64-fold.[3] If this rate of growth continues, China will become the leading producer of scientific publications by 2020.[4] China's Olympic triumphs flowed in part from its careful targeting of medal-rich sports like gymnastics, shooting and judo. In the same way, it has focused its research investment on disciplines where the opportunities are greatest. China's share of publications in the physical sciences and engineering has risen sharply. It has been particularly successful in nanotechnology, where one recent study found that 'by 2005, China had equalled or possibly even surpassed the US in terms of total output… of nanorelated scientific publications'.[5] The Chinese Academy of Sciences is ranked fourth in the world for nano citations after the University of California Berkeley, MIT and IBM.[6]

Increasing global investment in science

The UK's track record of scientific excellence brings with it a risk of complacency. The latest figures on prizes, patents, papers and citations typically reflect science conducted several years ago. But large investments in both advanced and emerging economies mean that the geography of science is changing (see Figures 2.1 and 2.2).[7] At the same time, new technologies, datasets and disciplines are transforming the way in which research is conducted. As this scientific century unfolds, the UK's leadership in research and higher education, and its broader economic prosperity, are far from secure.

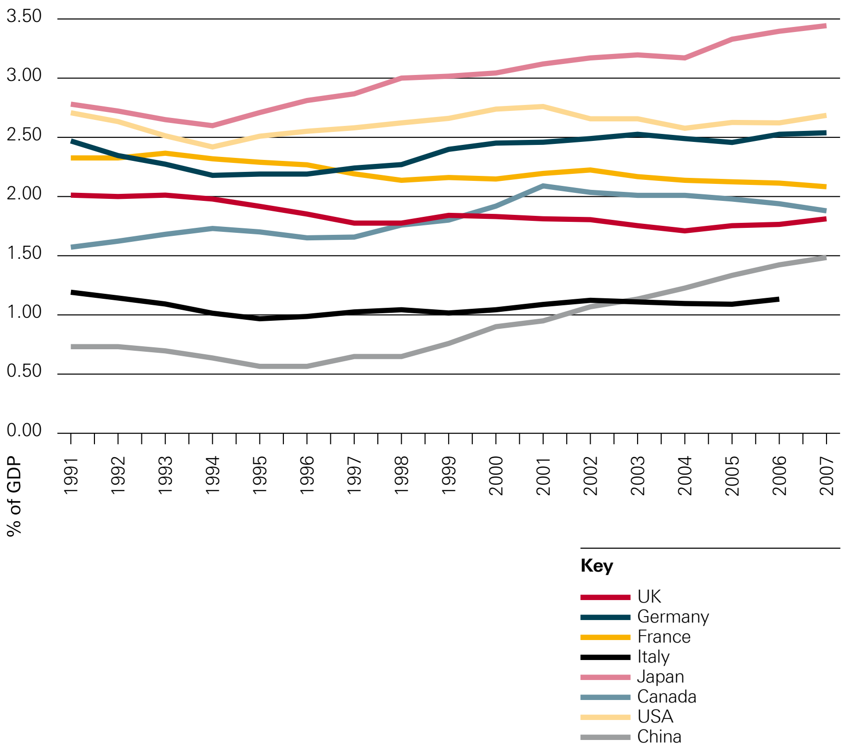
China may be the most compelling example of a country that was on the margins of international science ten years ago, and is now a pivotal hub in the flow of people, ideas and technologies around the world. However, it is far from alone.

In India, levels of R&D investment are also rising. There is a talent pool of 2.5 million new graduates every year in IT, engineering and the natural sciences. In 2008, India's Prime Minister Manmohan Singh announced plans for a 'quantum jump in science, education and research'. Singh pledged to open five new Indian Institutes of Science Education and Research, eight Institutes of Technology, seven Institutes of Management and 30 new universities. One million school pupils will each receive a science scholarship of 5,000 rupees (US$130) over the next five years, and 10,000 scholarships of 100,000 rupees per year will go to those taking science degrees.[9]

Brazil is now the world's fifteenth largest producer of scientific publications, up eight places in under a decade.[10] In November 2007, Brazil's President Lula announced an action plan for science and innovation, accompanied by US$20 billion of fresh investment, and its budget is set to rise further in 2011. Brazil's scientific publications are most concentrated in agriculture, biology and earth sciences, reflecting the importance of the country's natural resources.

Even the Middle East, which has traditionally lagged below global averages in science and technology, is showing signs of renewed ambition. Particular impetus is coming from energy-rich nations, which see science and innovation as the key to their long-term prosperity in the face of oil shortages and climate change. In 2009, Saudi Arabia opened the $10 billion dollar King Abdullah University of Science and Technology, which aims to become an international centre for medicine, pharmacology, computer science and engineering. The government of Qatar has built a 2,500-acre 'education city' on the outskirts of Doha and set a target of 2.8% of its GDP to be spent on research. And in 2008, the United Arab Emirates launched the Masdar Initiative, which aims to create a sustainable city with homes for 50,000 people and 1,500 businesses focused on renewable energy and sustainable technologies.

Figure 2.1 **National spend on R&D in selected OECD and comparator countries as a percentage of GDP, 1991-2005**[8]



1 OECD (2006) (Press Release). *China will become the world's second highest investor in R&D by end of 2006, finds OECD.* Organisation for Economic Co-operation and Development: Paris, France. 4 Dec 2006.

2 PRC State Council (2006). *Guidelines for the Medium and Long Term National Science and Technology Development Programme (2006-2020).* People's Republic of China State Council: Beijing, China.

3 Adams J, King C, Ma N (2009). Global Research Report: China. Research and collaboration in the new geography of science. Evidence (a Thomson Reuters company): Leeds, UK.

4 Adams J, King C, Singh V (2009). *Global Research Report: India. Research and Collaboration in the New Geography of Science.* Evidence (a Thomson Reuters company): Leeds, UK.

5 Appelbaum R and Parker R (2008). *China's bid to become a global nanotech leader.* Science and Public Policy **35**, 5, pp 319-334.

6 Liu L and Zhang L (2005). *Nanotechnology in China – now and in the future.* Nanotechnology Law and Business **399**.

7 Evidence Ltd (2009). *International Comparative Performance of the UK Research Base.* Department for Business, Innovation and Skills: London, UK.

8 OECD (2009). *Main Science and Technology Indicators (MSTI): 2009 Edition.* Organisation for Economic Co-operation and Development: Paris, France.

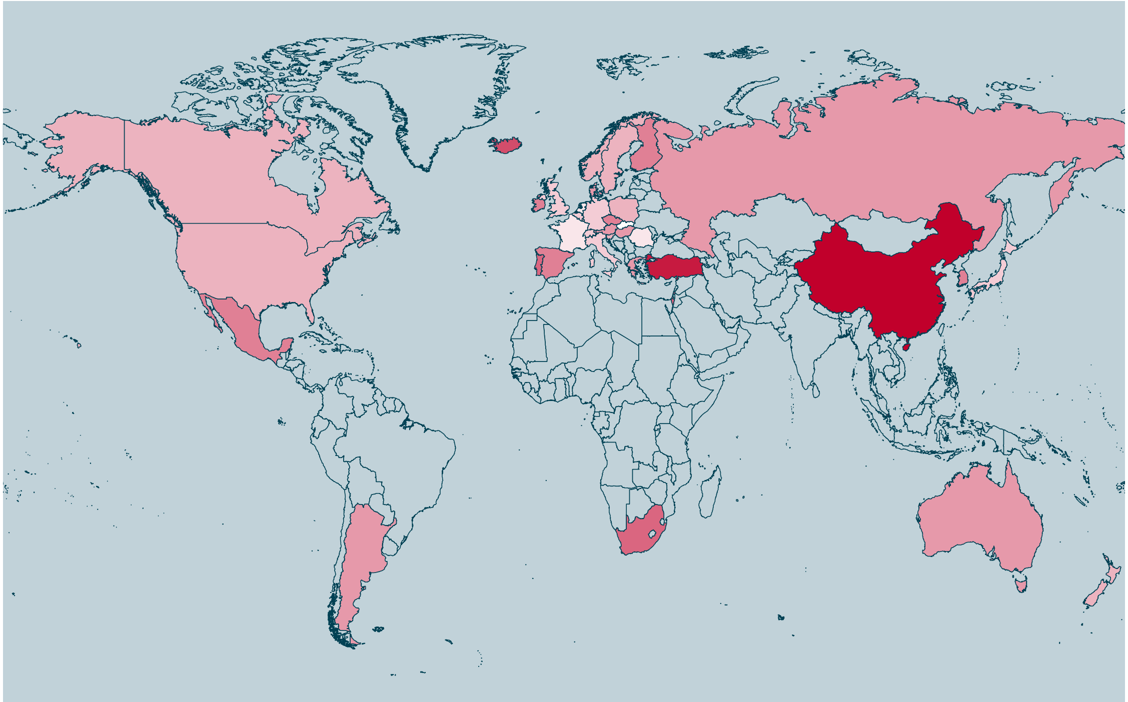
9 Jayaraman K (2008). *India aims for 'quantum jump' in science,* Nature **451**, 10.

10 Bound K (2008). *Brazil: The Natural Knowledge Economy.* Demos: London, UK.

PART 2

New frontiers of science

Figure 2.2 **Average annual percentage growth in R&D budgets, 1997-2007**[11]



Key Average annual % growth

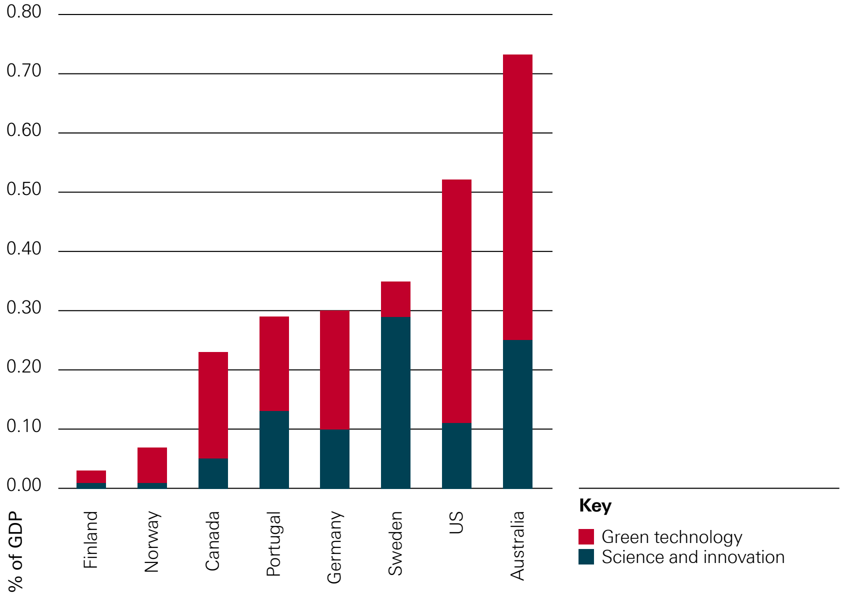
-2 18

Figures from Brouncker's paper on the compression of air under water, 1671

Innovating through the downturn

In the latter part of 2008 and early 2009, many governments outlined economic stimulus packages in response to the global financial crisis (see Figure 2.3). Science and innovation featured prominently.[13] For example, US President Obama pledged 'the largest commitment to scientific research and innovation in American history', on the basis that 'science is more essential for our prosperity, our security, our health, our environment, and our quality of life than it has ever been before'.[14] Some countries, notably South Korea, have targeted their investment at low-carbon technologies. The UK's own stimulus package did not make any specific investments in science and research, but the April 2009 Budget did include a new £750 million Strategic Investment Fund, £250 million for low-carbon technologies and an additional £50 million for the Technology Strategy Board.[15]

Figure 2.3 **Science and innovation investments in stimulus packages in select countries as a percentage of GDP**[12]



11 OECD (2009). *Main Science and Technology Indicators (MSTI): 2009 Edition.* Organisation for Economic Co-operation and Development: Paris, France.

12 OECD (2009). *Policy Responses to the Economic Crisis: Stimulus Packages, Innovation and Long-Term Growth.* Organisation for Economic Co-operation and Development: Paris, France.

13 *Ibid.*

14 Obama B (2009). Speech by US President Barack Obama at the 146th Annual Meeting of the US National Academy of Sciences.

15 HM Treasury (2009) (Press notice) *Building Britain's future.* 22 April 2009 HM Treasury: London.

As the world's economies have stabilised and started to move out of recession, several countries have announced further investment plans for science and innovation. The Australian science and innovation budget in May 2009 included a 25% increase on the previous year. In February 2010, the US Government confirmed an increase of 5.7% in the US Federal research and development budget for 2011.

France and Germany have also chosen to prioritise science and research as part of their strategies for economic recovery and growth. In the same week the UK's Pre-Budget Report announced a £600 million cut to UK higher education budgets, the French government made a fresh €35 billion investment in 'the knowledge economy and the green economy'. €11 billion of this is allocated towards the top French universities, in an effort to rival the success of the UK. As the French President Nicolas Sarkozy explained, 'we have lost market share, not to emerging countries, not to Brazil, India, China, but to our European neighbours.'[16] Following the German elections in September 2009, Chancellor Merkel's government announced that the Federal budget for education and research will rise by €12 billion by 2013. The government's goal is to create 'Bildungsrepublik', an 'educated and learning republic'[17] to build on Germany's existing strengths in knowledge exchange through the Fraunhofer-Gesellschaft and other intermediary institutions.

Evidence from previous downturns suggests that investing in the research base can reap rewards. Finland's recovery strategy following its deep recession in the early 1990s focused on science and innovation, and succeeded in shifting its economic base away from heavy industry towards knowledge-intensive sectors.[18]

Although the impact of recent investments remains to be seen, these countries are likely to become more attractive, not only to researchers, but also to companies investing in R&D. Here, emerging economies will also put the UK under pressure. In 2001, there were fewer than 100 R&D centres in China, but by the end of 2005 this had increased to more than 700.[19] The proportion of pharmaceutical patents naming Chinese and Indian researchers has increased fourfold since 1995.[20] Singapore has become a magnet for pharmaceutical companies, drawn by infrastructure such as A*Star's Biopolis. Questions remain about the extent to which such inward investments will strengthen indigenous scientific capacity, but some positive spill-over effects are inevitable.

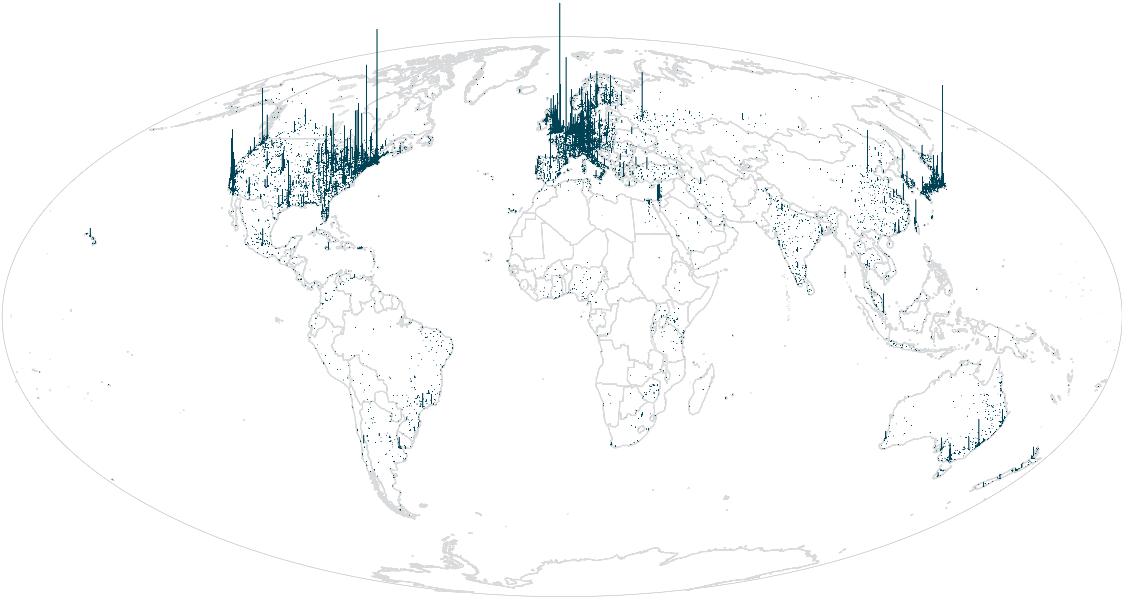
A gathering storm?

These changes in the geography of science have provoked concern in Europe and the USA.[21] In 2005, the US National Academies published a highly influential report –'Rising above the Gathering Storm' – which analysed trends in US science spending and training.[22] The predicted storm was the challenge to US scientific leadership posed by China, India and others, and their recommendations played an important part in building the case for recent increases in US investment.

Others argue that fears of the decline of US or European science are exaggerated. Research remains highly concentrated in relatively few places (see Figure 2.4). A study by RAND published in June 2008, concludes that the US 'continues to lead the world in science and technology… [It] accounts for 40 percent of total world R&D spending… produces 35 percent, 49 percent, and 63 percent, respectively of total world publications, citations, and highly cited publications, employs 70 percent of the world's Nobel Prize winners… and is the home of 75 percent of both the world's top 20 and top 40 universities.'[24]

The reality most likely lies between these two

Figure 2.4 **Where research takes place**[23]



Key

Number of papers produced by local institutions

16 France 24 (2009). *Sarkozy unveils €35 billion public spending spree.* France24.com.

17 German Government (2009) (excerpt). *Coalition Agreement between CDU, CSU and FDP. Chapter II: Bildungsrepublik Deutschland, Durch gute Bildung und starke Forschung* (pp 59–132). Courtesy of Helga Nowotny.

18 NESTA (2009). *Demanding Growth: Why the UK Needs a Recovery Plan Based on Growth and Innovation.* National Endowment for Science, Technology and the Arts: London, UK.

19 OECD (2008). *OECD Reviews of Innovation Policy. China* (p216). Organisation for Economic Co-operation and Development: Paris, France.

20 Wadhwa V et al. (2008). *The Globalization of Innovation: Pharmaceuticals: Can India and China Cure the Global Pharmaceutical Market.* Ewing Marion Kauffman Foundation: Kansas City, KS, USA.

21 Zakaria F (2008). *The Post-American World.* WW Norton and Company: New York, USA.

22 See: US National Academy of Sciences, National Academy of Engineering and Institute of Medicine (2005). *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.* The National Academies Press: Washington, DC, USA; Kao J (2007). *Innovation Nation: How America Is Losing Its Innovation Edge, Why It Matters, and What We Can Do to Get It Back.* Free Press: New York, USA.

23 Wagner C (2008). *The New Invisible College: Science for Development.* Brookings Institution: Washington, DC, USA. p. 72. Reprinted with permission.

24 Galama T & Hosek J (2008). *US Competitiveness in Science and Technology.* Prepared for the Office of the Secretary of Defense. RAND Corporation: Santa Monica, CA, USA.

positions. Emerging economies are starting from low bases, and still have some way to go to challenge the research strengths of the USA, Europe and Japan. It can be hard to understand a country's innovation potential just by looking at the statistics. According to one study, 'it is like being in a fairground hall of mirrors: the same statistics can simultaneously look very large or very small depending on your vantage point.'[25] Despite dramatic shifts in the capability of China and other emerging economies, the 'hardware' of investment and infrastructure is not yet matched by the 'software' of culture, values and creativity. For instance, in physics, China is fourth in the world in quantity of publications but 65th in terms of citations per paper.[26]

Rather than one scientific 'superpower' succeeding another, as the US declines and China rises, we are witnessing the emergence of an increasingly multi-polar, networked system of global science and innovation. The growing capabilities of other countries will clearly challenge the UK and the US in some disciplines and sectors. But it is short-sighted to view these developments primarily as a threat.

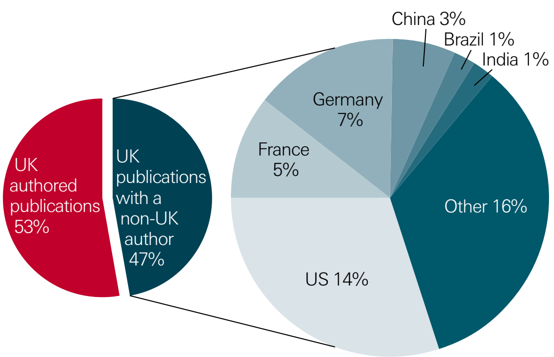
Efforts to strengthen national science and innovation systems remain vital for the UK, but must be accompanied by more creative and better-resourced mechanisms for orchestrating research across international networks, particularly in response to shared challenges such as climate change and food security. Linking with the outside world will increasingly be as important as 'sinking' investment into local research.[27] The Large Hadron Collider is one recent example of what can be achieved by working together: a scale of scientific investment and ambition that no one country could manage alone.

As explored in a recent Royal Society-AAAS report, scientific excellence and international diplomacy can reinforce one another.[28] Foreign policy objectives are often informed by science advice, and scientific collaboration can form a bridge between nations where political relations may otherwise be strained. The UK's Science and Innovation Network (SIN) is a good example of a government's ability to foster these links. Established in 2001 and based in 25 countries, this network of science attachés connects scientists and policy makers in the UK with their counterparts in other countries, showcasing the UK as a scientific hub, supporting collaboration and promoting science based solutions to global problems.

The UK's strengths as a hub for international science

UK science, as discussed in Part 1, remains near the top of scientific league tables. This attracts world class scientists to work or collaborate here. The quality of the UK's publications is enhanced by working with established scientific nations and with emerging economies. Recent figures from Thomson Reuters show that in 2007, 47% of the UK's scientific publications had a non-UK co-author (see Figure 2.5), up from 33% in 1999. The impact of these publications, measured by citations, is significantly higher than the UK average, which is itself 1.5 times the global average. UK publications with French, German and US co-authors have 1.5 times the UK average impact. Co-publications with Chinese and Indian authors are a little over the UK average, and Brazil-UK co-authored papers have an impact factor 1.3 times the UK average.[30]

Figure 2.5 **Percentage of UK publications co-authored with overseas collaborators**[29]



The UK's Research Councils encourage international collaboration, both through specific schemes, such as EPSRC's clean and renewable energy programmes with China and India, and through mainstream funding. EPSRC spent £141.3 million in 2008/09 on projects that mention international collaborators at the point of application; in 2002/03, this was just £15.5 million. Since 2005, EPSRC has also spent over £143 million on visiting fellowships to UK institutions. In 2007, the Economic and Social Research Council (ESRC) initiated a scheme in which up to 30% of a project's funding can be spent on foreign co-investigators. So far, ESRC has awarded £5.5 million to such projects.[31]

RCUK offices in Brussels, Washington, New Delhi and Beijing are another sign of the Research Councils' commitment to engaging with international science. Bilateral schemes such as the Science Bridges with the USA, China and India, the recent agreement signed with funders in Brazil and the new G8 multilateral research programme all reflect the UK's commitment to supporting international research.

Attracting talent to our global universities

UK universities also score well in global league tables. In the Shao Jiaotong Academic Ranking of World Universities 2009, the University of Cambridge is ranked fourth in the world, with the University of Oxford coming tenth, and a further nine universities into the top 100 (more than any other country after the USA).[32]

The UK also competes successfully to attract the best students onto masters and doctoral courses. Numbers of non-UK masters students at UK universities have quadrupled in the last 10 years and now account for over half of all masters students. Numbers of non-UK doctoral students have more than doubled.[33] The UK attracts 15% of all international doctoral students, second only to the USA. 42% of our postgraduate research students are international, compared to 35% in the US and 33% in France.[34] The flow of these students through the UK creates a valuable opportunity for the UK to influence and benefit from future developments in international science and innovation.[35]

25 Leadbeater C and Wilsdon J (2007) *The Atlas of Ideas: How Asian innovation can benefit us all.* Demos: London, UK.

26 Wilsdon J (2008). *The new geography of science.* Physics World. October 2008.

27 Wagner C (2008). *The New Invisible College: Science for Development.* Brookings Institution: Washington, DC, USA.

28 Royal Society (2010). *New Frontiers in Science Diplomacy. Navigating the Changing Balance of Power.* Royal Society: London, UK.

29 Evidence Ltd (2009). *International Comparative Performance of the UK Research Base.* Department for Business, Innovation and Skills: London, UK.

30 *Ibid.*

31 Evidence provided by RCUK.

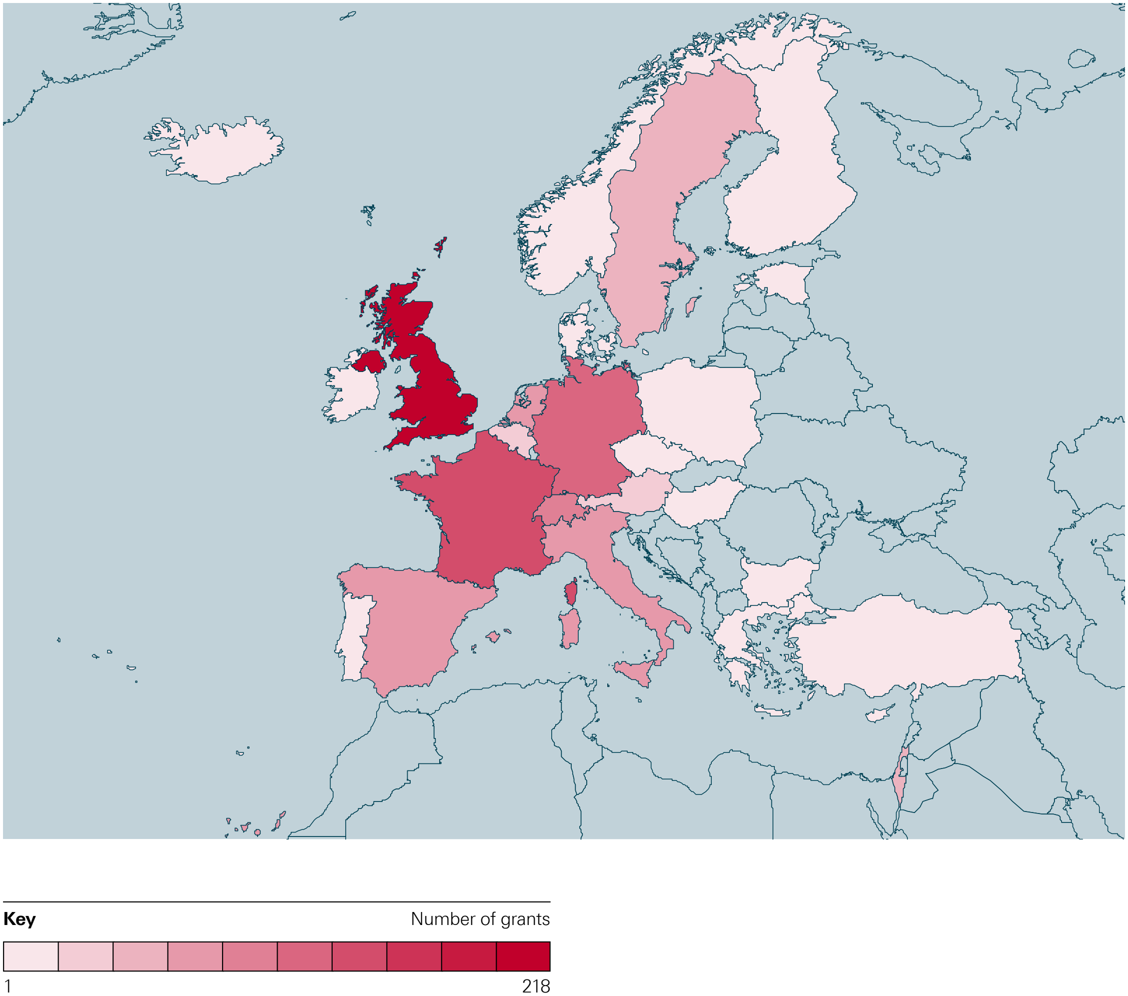
32 Center for World-Class Universities and the Institute of Higher Education of Shanghai Jiao Tong University, China (2009). *Academic Ranking of World Universities (ARWU).* Available online at: http://www.arwu.org/ARWU2009.jsp

33 Royal Society (2008). *A Higher Degree of Concern.* The Royal Society: London, UK.

34 UK HE International Unit (2008). *The UK's Competitive Advantage: The Market for International Research Students.* UK Higher Education International Unit: London, UK.

35 Royal Society (2008). *A Higher Degree of Concern.* Royal Society: London, UK.

Figure 2.6 **Numbers of European Research Council grants per country, 2007-2009**[41]



Sketches of eyes/light refraction

The European dimension

Collectively, the 27 nations of the European Union compete strongly with the USA. The US is home to 26.8% of the world's researchers and the EU to 23%; the USA produces 39.7% of patent applications, the EU27 36%. Between 2000 and 2006, EU R&D investment increased by 14.8% in real terms, compared with 10.1% in the USA. In 2006, 37.6% of the world's publications had an EU co-author, while 31.5% had a US co-author.[36]

The UK contributes heavily to the strength of these EU27 figures on research and innovation, and benefits from the structures that have been put in place to encourage closer European cooperation. The UK academic community received 8.5% of the total budget of the sixth Framework Programme (FP6) – a quarter of the total funding that went directly to Europe's academic community as a whole.[37] The UK's performance in FP7 to date is similarly strong, with 14.6% of the total funding (€1.35 billion), and involvement in 43.2% of all grant applications.[38]

The UK is particularly successful at attracting researchers to work here. Between 2003 and 2006, the UK hosted the highest share of European Commission Marie Curie Intra-European Fellows. 35% chose to come to the UK for their fellowships compared with 15% to France and 10% to Germany.[39] The UK has also benefited from the European Research Council (as part of FP7), with 19% of Starting Grants and 23% of Advanced Grants hosted here[40] (see Figure 2.6).

Between 2007 and 2013, FP7 will provide €50.5 billion of funding for people, projects and research infrastructure across Europe.[42] This scale of funding means that European research mechanisms must now be considered an important part of the UK's science funding landscape. The UK would benefit from playing a full role in shaping the instruments and priorities for the eighth Framework Programme, which will run from 2013.

36 European Commission (2008). *FP6 Final Review: Subscription, Implementation, Participation.* European Commission: Brussels, Belgium.

37 HM Government (2007). *Government Response to the House of Commons Science and Technology Committee Seventh Special Report.* Stationery Office: London, UK.

38 EU Cordis database (2009). FP7 grants agreements and participants. Data obtained from Department for Business, Innovation and Skills.

39 European Commission (2008). *A More Research-Intensive and Integrated European Research Area; Science, Technology and Competitiveness Key Figures Report 2008/2009* (pp 99–123). European Commission: Brussels, Belgium.

40 See: erc.europa.eu/index.cfm?fuseaction=page.display&topicID=165. Starting grants are for early researchers and Advanced grants for established researchers.

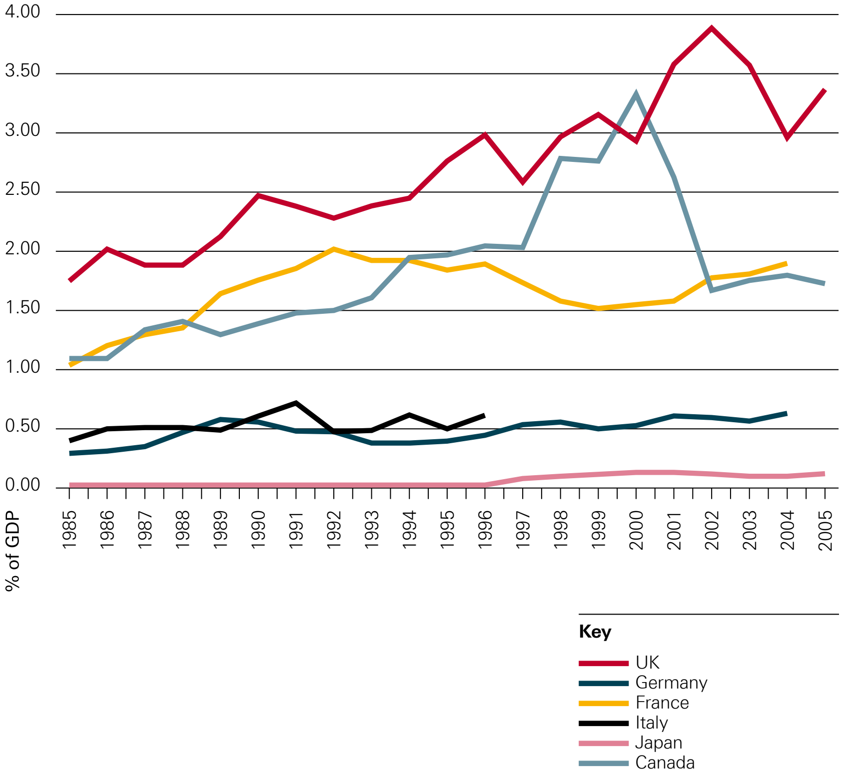
41 *Ibid.*

42 See: cordis.europa.eu/fp7/budget_en.html#

Attracting investment

The UK attracts a higher share of its R&D from overseas than anyone else in the G8[43] (Figure 2.7 illustrates this strong performance in comparison with selected countries). Foreign firms seeking to locate research are particularly enthusiastic about the UK's leading university science departments, and there is a direct correlation between a department's Research Assessment Exercise score, and its ability to attract research labs nearby.[45]

Figure 2.7 **Domestic research and development funded from abroad as a percentage of gross domestic product, 1985-2005**[44]



The UK's universities are themselves a substantial industry. In 2007/08, UK universities generated over £59 billion of output and created more than 668,500 full time jobs. Export earnings from the UK's higher education sector were £5.3 billion, significantly bigger than other high value-added services such as advertising (£2.4 billion) and telecommunications (£4.9 billion). International students at UK universities spent 14% of all overseas expenditure by visitors to the UK.[46]

Globalisation is intensifying competition but science, location and history still matter[47] because much of the knowledge that underpins innovation is tacit.[48] Talent attracts talent, and people need conducive environments in which to gather and share ideas. This is most obvious in places like Silicon Valley, but is increasingly visible in the innovation clusters around the UK's world-class universities.[49]

Threats to the UK as a hub for international science

Despite its current position, there are worrying signs that the UK may become a less attractive place to do research. A recent report by Universities UK (UUK) identified a need to better promote UK doctorates overseas to meet challenges from countries such

Red chalk drawing of sand, Antoni Van Leeuwenhoek, 1704 as Germany and the Netherlands, who are now providing doctoral programmes in English, and Belgium and Finland, who provide more attractive financial packages for researchers.[50] The report also suggested that universities may be over-reliant on particular markets for international students (e.g. arts and humanities students from the US, and engineering and technology students from China).

With France and Germany increasing their university and research investments, the UK's position as a partner of choice in Europe (and by extension, globally), could be undermined. Scientists themselves aim to collaborate with the best of their peers, wherever they are based. Policy and funding can either enable or hinder this bottom-up process.

The UK government has a number of bilateral science and innovation agreements with countries such as Russia, Japan, China, India and Brazil. China and India, in particular, adopt a more top-down approach to research funding than the UK. By relying primarily on responsive mode funding, and relatively small scale bilateral research projects, the UK government is often unable to respond to opportunities to invest in strategic, large-scale research projects. Science Bridges schemes and other Research Council initiatives to encourage collaboration are welcome attempts to meet this challenge and will need to be expanded and replicated elsewhere in the future.

Open science

Science thrives on openness – the free exchange of ideas, knowledge and data. Changes to the way that information is shared are already accelerating developments in certain disciplines and creating new approaches to research. This openness can create a tension with the need to capture and exploit intellectual property.[51] But it also presents an opportunity for scientific collaboration and innovation.

Most research is now performed by teams rather than lone scientists.[52] In areas like astronomy and high-energy physics, increasingly powerful and expensive experimental facilities mean that countries and research groups are more likely to share investments and results, CERN being the most prominent example. As the quantity of data produced by research increases exponentially and the sharing of that data becomes easier, computer science is blending with other disciplines, enabling new forms of data-driven 'e-science'.[53]

43 European Commission (2008). *A More Research-Intensive and Integrated European Research Area; Science, Technology and Competitiveness Key Figures Report 2008/2009* (pp 99–123). European Commission: Brussels, Belgium.

44 OECD (2009). *Main Science and Technology Indicators (MSTI): 2009 Edition.* Organisation for Economic Co-operation and Development: Paris, France.

45 Abramovsky L, Harrison R, Simpson H (2007). *University research and the location of business R&D.* Economic Journal **117**, 519.

46 Universities UK (2009). *The Impact of Universities on the UK Economy.* Universities UK: London, UK

47 Nesta (2008). *History Matters.* National Endowment for Science, Technology and the Arts: London, UK.

48 Howells J (2002). *Tacit knowledge, innovation and economic geography.* Urban Studies **39**, 5–6, pp 871–884.

49 Nesta (2007). *Innovation and the City.* National Endowment for Science, Technology and the Arts: London, UK; Nesta (2009). *The connected university.* National Endowment for Science, Technology and the Arts: London, UK.

50 Universities UK (2009). *Promoting the UK Doctorate: Opportunities and Challenges.* Universities UK: London, UK.

51 Royal Society (2003). *Keeping Science Open: The Effects of Intellectual Property Policy on the Conduct of Science.* Royal Society: London, UK.

52 Wuchty S, Jones B, Uzzi B (2007). *The increasing dominance of teams in the production of knowledge.* Science **316**, 5827, pp 1036–1039.

53 See: Microsoft Research (2006). *Towards 2020 Science.* Microsoft Research: London, UK; and www.rcuk.ac.uk/escience.

In molecular biology, for example, technical advances in DNA sequencing, proteomics and structure determination have led to an avalanche of genome, proteome, microarray and functional genomic data.[54] As with computing power, the time and money required for DNA sequencing is falling exponentially. By 2008, five years after the first human genome was sequenced, the Wellcome Trust Sanger Institute was sequencing 15 complete human genomes each week.[55] These electronic data resources are now a major part of the molecular biology research infrastructure, which some describe as a third stream of scientific capital, alongside people and infrastructure.[56]

The growth of the internet has raised expectations that information should be available at any time, anywhere, for free. Scientific journal publishers are moving towards opening access to their journals to new audiences, particularly researchers in poor countries. The argument that publicly-funded research should be publicly accessible is hard to resist. Open access has significant advantages for those within and outside the scientific community.[58]

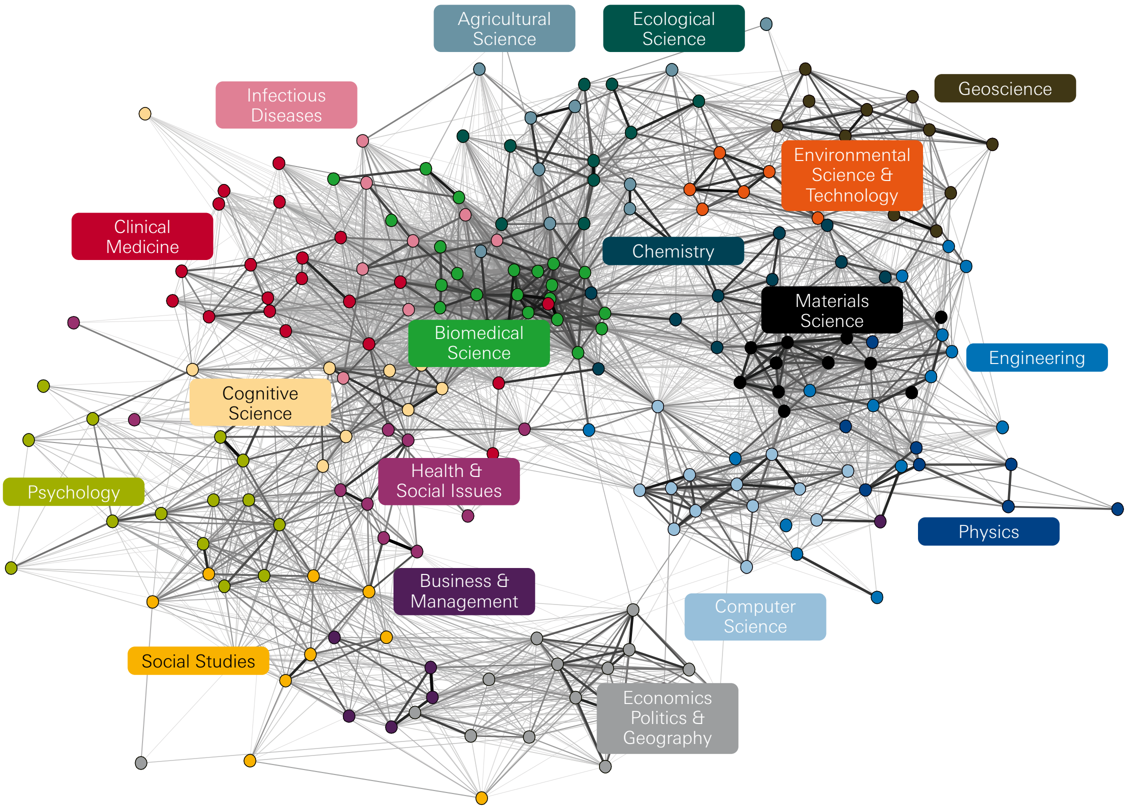
Interdisciplinarity

As science developed in the 19th and 20th centuries, it began to organise itself into ever more specialist disciplines. But interdisciplinary research is now becoming more prominent.[59] The boundaries between previously distinct fields are starting to blur as ideas and tools are imported from one discipline to another (see Figure 2.8). This is not a new phenomenon. Biochemistry and cognitive science, to take two examples, began as hybrids, but are now considered disciplines in their own right.

Outside universities, innovation often happens at the margins and intersections of disciplines. According to the US National Academies, interdisciplinarity is powered by four drivers: ‘the inherent complexity of nature and society, the desire to explore problems and questions that are not confined to a single discipline, the need to solve societal problems and the power of new technologies.’[61]

Emerging areas such as nanotechnology and synthetic biology span the boundaries between the physical and life sciences, and between science and engineering. They challenge the way that science is funded, conducted, communicated, evaluated and taught (see Case study 2.9). Connections with and between the natural sciences and the social sciences, arts and humanities will also be increasingly vital for innovation, particularly in the services sector. Universities, research funders and systems of research assessment are slowly adapting to interdisciplinarity, but still often reinforce disciplinary borders and prohibit more creative collaborations.[62]

Figure 2.8 **Global map of science by discipline**[60]



This map represents the enormous cross-disciplinary complexity of current scientific research. It depicts connections between disciplines according to cross-citations in journals in 2007. Colours and labels represent broad disciplines. Some fields, such as mathematics, are so pervasive throughout the research system that they have no single label.

54 Lopez *et al.* (2002). *The European Bioinformatics Website: A New View.* Bioinformatics Applications Note **19**, 4, 546–547.

55 Wellcome Trust Sanger Institute (2008) (Press release). *15 human genomes each week.* Wellcome Trust Sanger Institute: Cambridge, UK. 1 July 2008.

56 Wouters P & Schroder P (eds.) (2003). *The public domain of digital research data: Promise and practice in data sharing*: NIWI-KNAW: Amsterdam, NL.

57 EBI (2009). *Annual Scientific Report 2009.* European Bioinformatics Institute: Cambridge, UK.

58 See European Commission (2008). *Open Access, Opportunities and Challenges*. European Commission: Brussels, Belgium. For more on the specifics of open access, see Universities UK and the Research Information Network (2009). *Paying for open access publication charges. Guidance for higher education and research institutions, publishers and authors.* A report by Universities UK and the Research Information Network.

59 Hicks D & Katz J (1996). *Where is science going?* Science, Technology & Human Values **21**, 4, 379–406; Nowotny H, Scott P, Gibbons M (2001). *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty.* Polity Press: London, UK.

60 Rafols I, Porter A, Leydesdorff L (2009). *Science overlay maps: a new tool for research policy.* SPRU Electronic Working Papers series, Paper no 179.

61 US National Academy of Sciences, National Academy of Engineering and Institute of Medicine (2005). *Facilitating Interdisciplinary Research.* The National Academies Press: Washington, DC, USA.

62 Royal Society (2009). *Hidden Wealth: The Contribution of Science to Service Sector Innovation.* Royal Society: London, UK.

Case study 2.9 **Interface journal**

In May 2004 the Royal Society launched *Interface*, its first new journal for over 150 years. It was a response to pressure from scientists who were finding few places to publish interdisciplinary work that bridges the physical and life sciences.[63] *Interface* publishes work which is hard to pigeonhole, for example the mathematical modelling of infectious diseases, or the engineering of new organisms.

Rather than shoring up the boundaries between fields, *Interface* acknowledges their blurring. Many scientists have embraced the journal as a key forum for their work. The rapid emergence of areas such as synthetic biology has brought together authors from engineering, biology, computer science and elsewhere. In less than three years, *Interface* became the fourth most highly-cited interdisciplinary journal in the world, behind *Science*, *Nature* and the *Proceedings of the National Academy of Sciences*. The number of articles submitted to the journal each year has grown fivefold. Plans are now in place for *Interface Focus*, a cross-disciplinary journal that will collect articles on particular themes.

Rising to the challenge

In the first decade of this scientific century, the UK has managed to build on its foundations of excellence to retain its status as a leading scientific nation. But securing our future prosperity will require us to keep running just to stand still, through continued investment and attention to impact, commercialisation and innovation. 21st century science and innovation policies must also be genuinely international, and responsive to global flows and competition for talent, ideas and investment. Crucially, they must include strategies for internationalising the research base.

The recommendations and actions that form the third part of this report identify priority areas for government action. Taken together, they provide a roadmap for UK science and innovation policy that builds on our strengths and targets areas of weakness.

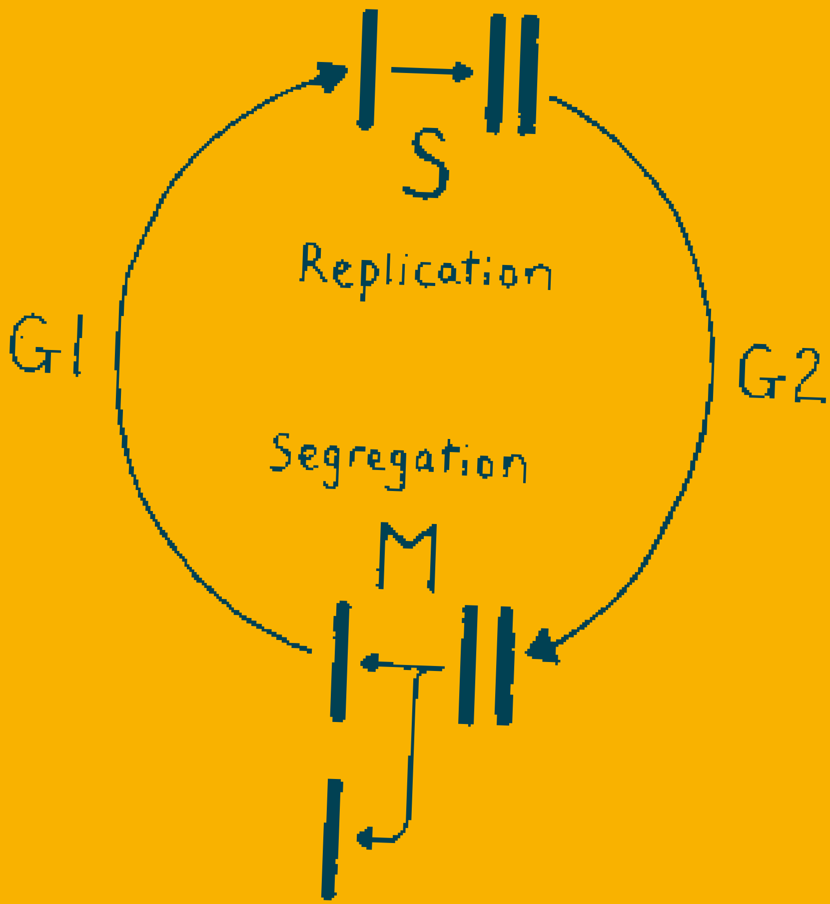
The first recommendation provides the foundation on which all the others are built. Science provides a route to economic revival and growth. Recent investments in the science base must therefore be sustained over the long-term. The five subsequent recommendations and actions focus on, in turn, supporting excellent scientists at all stages of their careers; improving the way that government manages and uses science; taking a strategic approach to international collaboration; bringing science to bear on global challenges; and, finally, the education of young people in science and mathematics.

Figure from Newton's 'Optiks', Book 1, part 1, Plate II

63 Royal Society Physical Sciences Publishing Programme (2002). Market Research Report. Royal Society: London, UK.

PART 3

Recommendations



This is a diagram of the cell cycle sketched by Sir Paul Nurse FRS, the 2001 Nobel Prize Laureate in Physiology or Medicine, outlining the main events that occur when cells divide and replicate. Our understanding of this most fundamental of cellular processes has resulted in the development of several cancer drugs currently in clinical trials. © Paul Nurse 1989.

Recommendation 1

Put science and innovation at the heart of a strategy for long-term economic growth

PART 3

Recommendations

Actions

- **Create a new long-term framework for science and innovation committing to increased expenditure**
- **Outline spending plans over a fifteen year period (2011-2026)**
- **Prioritise investment in scientific capital – including infrastructure and skills**
- **Expand the R&D tax credit**

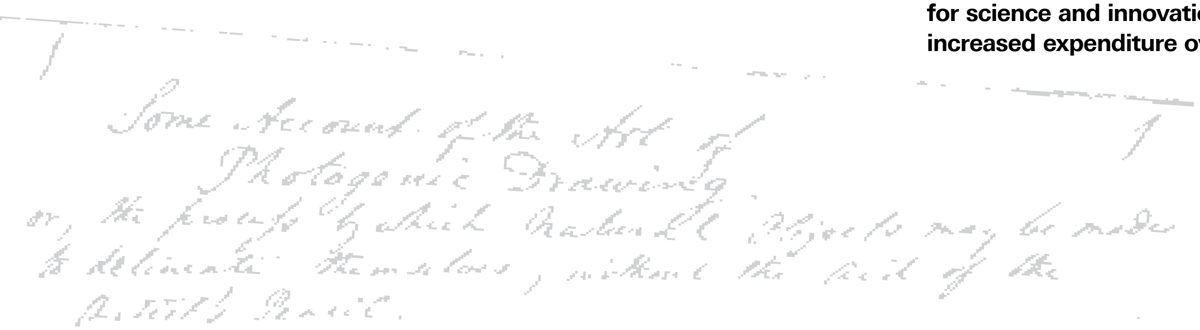
Science, technology and innovation are increasingly vital to the health and wealth of nations. In its research base, the UK has a national asset envied throughout the world. So we enjoy a head start in the economic 'race to the top'.[1] The weakened state of public finances will force hard investment choices in the short term, but our science and innovation capabilities must be prioritised as part of any strategy for long-term prosperity and sustainability.

Laying the foundations for future growth

Following the global financial crisis, as the UK seeks a more diverse, balanced and sustainable economy, science is an area of competitive advantage.[2] More than a decade of investment has revitalised the UK's research base after a long period of neglect. Protecting and strengthening this asset should be prioritised in order to secure future growth and competitiveness.

Public investment in science and innovation creates jobs, boosts productivity, underpins private sector R&D spending and attracts substantial foreign investment. The industrial revolution, the manufacturing revolution and the information revolution were all underpinned by science and technology.[3] The UK must be positioned to contribute to and benefit from the growth of the next wave of disruptive technologies.

However, the UK's current position is under threat. Many countries are rapidly increasing their research budgets to accelerate their own return to growth. If the UK stands still now, it will be impossible to remain at the forefront of global science. In 2004, the Government's Ten-Year Framework for Science and Innovation promised long-term investment. This project must be seen through to completion, and extended beyond its original deadline of 2014. **We therefore recommend that the Government creates a renewed investment framework for science and innovation, committing to increased expenditure over the long-term.**



'Some account of photogenic drawing', William Henry Fox Talbot, 1839 © The Royal Society

The ringfenced science budget is vital, and already guarantees a degree of autonomy for scientific research. The other pillar of the dual-support system, the unrestricted block grants allocated through the Higher Education Funding Councils, is just as important. This dual-support system provides a stable platform on which universities can plan, develop their own missions and build up capacity.

Scientific infrastructure is particularly vulnerable to behind-the-scenes budget cuts. University labs and world-class facilities, such as those at Daresbury, Rutherford-Appleton and the planned UK Centre for Medical Research and Innovation in London, need ongoing investment in order to attract the best projects and researchers. The UK science and innovation ecosystem must be given a clear, long-term framework within which to plan, build and compete globally. **A strategy for science and innovation should cement the UK's leadership for a generation, looking fifteen years ahead, from 2011 up to 2026.**

False economy in an age of austerity

Having built up our stock of knowledge and expertise, we cannot rely on reputation to protect it. Investment choices have been made harder by the recent global recession and its impact on public finances. But cuts to science and innovation spending are a false economy. Science and innovation are investments that are central to short-term economic recovery and, more importantly, to long-term prosperity and growth. Estimates from the Institute for Fiscal Studies point to the need for public spending cuts of around 6.4% per year between 2011 and 2014.[4] Such cuts, if applied to science, would threaten the UK's position at the forefront of global science and risk our long-term economic health. The science and innovation ecosystem is fragile: hard to build and maintain but all too easy to damage through neglect.

History provides a stark warning. In the mid-1980s, year-on-year cuts to UK university science brought scientists' morale to an all-time low. Reductions in research funding were exacerbated by larger cuts to teaching and infrastructure budgets. Researchers struggled to remain at the cutting edge of their disciplines, using old equipment that they could not afford to replace. A stagnant research environment drove many leading UK scientists to the US.[5] In 1986, 1,500 scientists and engineers, including 100 Fellows of the Royal Society, established a new organisation called 'Save British Science'. They took out an advert in *The Times* warning that 'Whole areas of research

1 Lord Sainsbury of Turville (2007). The Race to the Top: *a Review of Government's Science and Innovation Policies.* The Stationery Office: London, UK.

2 HM Government (2010) *Going for Growth: Our Future Prosperity.* Department for Business, Innovation and Skills: London, UK.

3 See: Freeman, C and Louca F (2001). *As Time Goes By: From the Industrial Revolutions to the Information Revolution.* Oxford University Press: Oxford, UK; Schumpeter J (1939). *Business Cycles.* McGraw-Hill: New York, NY, USA.

4 BBC (2009). *Darling 'must cut £36bn', IFS think tank says.* BBC News Online, 10 December 2009. Available online at: news.bbc.co.uk/1/hi/8406670.stm

5 For an account of the 1980s cuts, see Sharp M (2003). *The UK experiment—science, technology and industrial policy in Britain 1979-2000. In: Innovation Policies in Europe and the US—The New Agenda.* Biegelbauer P & Borrás S (eds). Ashgate: Farnham, UK.

are in jeopardy… There is no excuse: rescue requires a rise in expenditure of only about one percent of Government's annual revenue from North Sea oil. We can and must afford basic research.'[6]

At the time, many of the UK's competitors were scaling back their own investments in science and innovation. This is no longer the case. Our long-term prosperity demands that we keep pace with the investments of others. Recent reductions in the HEFCE budget echo the infrastructure cuts of the 1980s. There needs to be a clear timetable for the reversal of these cuts.

Alongside scientific knowledge, the people that science produces are just as important a resource for the productivity of the wider economy.[7] The benefits of scientific skills and knowledge extend far beyond high-tech sectors.[8] Analytical and problem-solving skills are becoming more important in insurance, business services, retail and the creative industries. As scientifically-trained people take different paths into the economy, the ripples of investments in science spread far and wide. **We recommend that any future science and innovation investment strategy puts scientific skills and infrastructure at its core.**

Increasing our innovation performance

Investments in science should run alongside coherent innovation policies, which improve knowledge exchange, accelerate the emergence of new markets and firms and improve business productivity. The last decade has seen real advances in mechanisms for knowledge transfer, translation and commercialisation. Government must continue to support the channels through which investments in knowledge and skills create value.

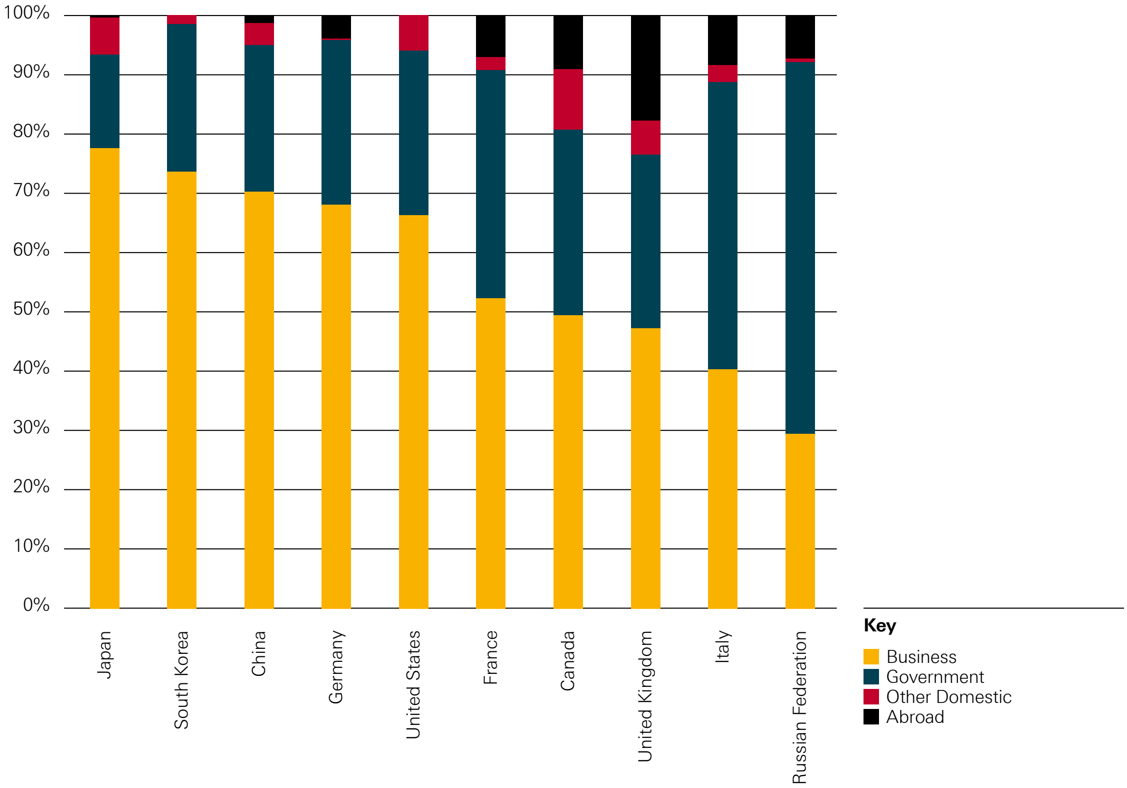
The importance of 'hidden' innovation occurring outside traditional research labs and high-tech companies is now widely recognised.[9] But more needs to be done to ensure that policy reflects the sectoral mix of the UK economy. Initiatives need to support innovation across the whole economy, particularly in neglected areas such as services and the public sector.

Firms are increasingly outward-looking in their approach to innovation, presenting an opportunity for universities that are willing and able to respond. Knowledge exchange between universities and companies is increasingly successful, but remains poorly understood.[10] Future innovation policies must give greater recognition to universities' informal business engagement alongside more visible interactions.

The UK has an admirable record in attracting R&D investment from abroad, in part because of our world class universities. However, UK companies still spend significantly less on R&D than those in other countries (see Figure 3.1.1), limiting our capacity for innovation. There need to be coherent policies for increasing business R&D, particularly in those sectors and industries with low levels of investment. **We recommend that the R&D tax credit is expanded.**

Sketches from paper 'Pulsars – Basic Problems', April 1982 © The Royal Society

Figure 3.1.1 **Share of R&D expenditure by funding source**[11]



6 The Times (1986). *Save British Science* (Advertisement) 13 Jan 1986.

7 HM Treasury (2006). *Leitch Review of Skills, Prosperity for all in the global economy – world class skills.* The Stationary Office: London, UK.

8 Royal Society (2009). *Hidden wealth: the contribution of science to service sector innovation.* Royal Society: London, UK.

9 Nesta (2007). *Hidden Innovation, How innovation happens in six 'low innovation' sectors.* National Endowment for Science, Technology and the Arts: London, UK.

10 Royal Society (2009). *Hidden wealth: the contribution of science to service sector innovation,* Royal Society: London, UK; PACEC (2009). *Evaluation of the effectiveness and role of HEFCE/OSI Third Stream Funding: culture change and embedding capacity in the Higher Education sector toward greater economic impact. A report to HEFCE by PACEC and the Centre for Business Research, University of Cambridge.* Higher Education Funding Council for England: Bristol, UK.

11 OECD (2009). *Main Science and Technology Indicators (MSTI): 2009 edition.* Organisation for Economic Co-operation and Development: Paris, France.

Recommendation 2

Prioritise investment in excellent people

Actions

- **Direct a greater proportion of Research Council funding to investigator-led research**
- **Increase the length and quality of UK PhD training**
- **Support transferable skills training for researchers**
- **Increase the number of postdoctoral fellowships**

To maximise the impacts of research investments, excellent scientists must be given the opportunity to pursue their curiosity. Research funders around the world are increasingly aware of this, shifting the balance of their funding away from *projects* towards *people*. Focussing funding on people, through grants and fellowships, has two clear advantages: it produces creative, world-class science and it provides career flexibility, encouraging the best researchers from the UK and elsewhere to stay in science.

The conventional approach to research funding is to support pre-defined projects, programmes and research institutes. But the benefits of research are often serendipitous and may not match those envisaged in a grant proposal. Scientists need flexibility to exploit the new opportunities and questions that emerge from their research. This is why the Royal Society awards long-term grants to excellent individuals, with minimal bureaucracy.

In the US, there is some evidence of the success of investigator-focused funding. The Howard Hughes Medical Institute (HHMI) Investigator Program provides long-term funding to individuals. When compared with scientists of equal calibre receiving conventional funding, HHMI investigators are more productive and more likely to conduct research in frontier areas (see Figure 3.2.1).[1]

The Wellcome Trust has recently announced a similar scheme, moving away from project and programme funding. Their assessment is that larger, longer, more flexible grants will allow researchers to take risks and reap bigger rewards.[3] The European Research Council (ERC) also follows this model.[4] The ERC was set up to support cutting-edge research by allocating its funds to excellent individuals in any area. Although the ERC is only three years old, it is already regarded as a success. France, Italy, Spain, Switzerland, Sweden and others are now using the ERC assessments as an indicator of quality to offer grants to their domestic researchers.[5]

The UK Research Councils have their own New Investigator and First Grant awards.[6] But this funding is still at a low level and does not allow the research freedom of an ERC grant.[7] A flexible and responsive research funding system must remain carefully balanced and continue to support projects, but there now needs to be greater emphasis on autonomy for excellent individuals, particularly in the physical sciences and engineering, where researchers cannot access the Wellcome Trust's funding schemes.

We recommend that the UK Research Councils direct an increased proportion of their responsive-mode budgets to investigator-led research awards.

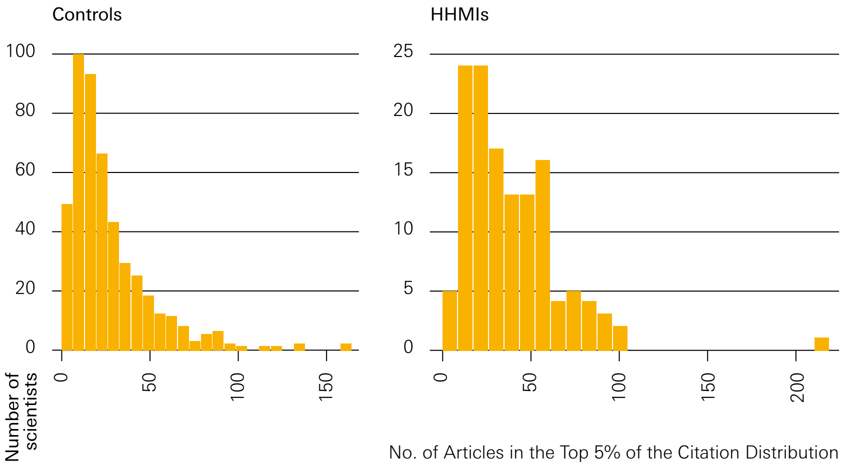
Maintaining the quality of PhD education

A sustainable science base demands a certain quantity of PhD-qualified entrants, but the quality of these people is just as important. The UK's universities are currently popular with foreign students. The 12% increase in PhD students between 2000 and 2006 was almost entirely due to applicants from overseas.[8] As global competition intensifies, the UK must improve the quality and attractiveness of its PhD education. Our slow progress towards the 8-year average length of time to PhD that is becoming the norm across Europe (the Bologna benchmark) is therefore a cause of concern.[9] Universities will be forced to make difficult choices about PhD education in the coming years, balancing quantity against quality.[10] Different subjects and institutions will have different requirements. **We recommend that universities are given sufficient resources and flexibility to increase the length and quality of their PhD courses.**

Figure 3.2.1

Increased quality of HHMI outputs[2]

HHMI funded scientists are more likely to produce highly cited work, as measured by the number of their articles cited in the top 5% of all articles published by both control and HHMI groups.



1 Azoulay P, Zivin J and Manso G (2009). *Incentives and Creativity: Evidence from the Academic Life Sciences.* NBER Working Paper No. 15466. The National Bureau of Economic Research: Cambridge, USA.

2 *Ibid.*

3 See: www.wellcome.ac.uk/Funding/investigator-awards/index.htm

4 European Commission (2005). *Frontier Research: The European Challenge, High-Level Expert Group Report.* European Commission Community Research: Brussels, Belgium.

5 European Research Council Review (2009). *Towards a world class Frontier Research Organisation. Review of the European Research Council's Structures and Mechanisms.* European Commission: Brussels, Belgium.

6 See: www.rcuk.ac.uk/cmsweb/downloads/rcuk/researchcareers/cir/investigators.pdf

7 Evidence provided by RCUK. In 2008/09, EPSRC gave £34.3 million to new investigators, NERC provided £1.2 million and in 2008 BBSRC handed out £20.6 million.

8 Universities UK (2009). *Research report: Taught postgraduate students: market trends and opportunities.* Universities UK: London, UK.

9 Royal Society (2008). *A Higher Degree of Concern.* Royal Society: London, UK.

10 This is currently the subject of a review led by Professor Adrian Smith FRS. See: www.bis.gov.uk/postgraduate-review

Beyond research skills

As the demands of careers change over time, early careers scientists need to acquire a broader range of skills (see Box 3.2.2). Since 2005, universities have been allocated around £22m per year for transferable skills development, which has already had a tangible impact.[11] The number of researchers on fixed-term contracts participating in transferable skills training doubled between 2006 and 2009.[12] Funding for such activities is now under threat. **We recommend the continuation and further development of a transferable skills programme. This should, in time, become an integral part of research career development for all researchers.**

Observations on duckweed.
Antoni Van Leeuwenhoek to
The Royal Society, 25 December 1702
© The Royal Society

Box 3.2.2 **Focus Groups with recent PhDs**

As part of this study, The Royal Society ran a set of focus groups with recent PhD graduates, concentrating on the factors that pull and push graduates into and away from scientific careers. These highlighted the extent to which career flexibility is critical. One participant, who recently left science, summed up his reasons as follows:

‘There were only a few labs in the world that worked on what I was doing. If I didn’t get the funding to stay where I was I would have had to have moved abroad… I couldn’t see myself doing that after the age of 30.’

Another, who stayed, described the painful insecurity of postdoctoral work as a cycle where ‘the passion gets weaker and weaker as the fight to get a job becomes more difficult.’

Some responses suggest that career support courses have worked well.[13] ‘It shows you how to leverage your PhD to the best of your ability.’ But there was a common feeling that attending a course ‘was frowned upon by the academics’. Employers outside science may be more appreciative of transferable skills training, but there were widespread complaints that PhD training was misunderstood: ‘the people in these industries look at you and say “why didn’t you get out sooner?”.’

Some pointed to a cultural gap between other sectors and academia. Closing this will require a more substantive interaction between academic and non-academic employers.

Fellowships for young scientists

Creative science, particularly in mathematics, often comes from younger scientists. But for many researchers, the years immediately following a PhD are uncertain, with short research contracts and intense competition for permanent university posts. Factors likely to drive the best young scientists away from a career in research include poor job security, limited opportunities for career progression, uncompetitive salaries and a lack of flexibility with regards to location, career breaks and movement between academia and industry.[14]

Increasing the availability of 5-8 year fellowships would strengthen the foundations of research careers.[15] Royal Society fellowships, which follow this model, have been shown to keep the most talented in science.[16] But with a success rate of around 6%, the Royal Society is forced to turn away many excellent researchers every year. The Research Councils only spend a small percentage of their budget on fellowships.[17] **We recommend increasing the number of fellowships specifically targeting excellent post-doctoral scientists.**

Standard academic career paths tie young scientists to institutions, discouraging mobility. Fellowships allow scientists to move between institutions, helping to support the changing needs of the modern scientists and their families, and encouraging the best science.[18] Research careers that rigidly follow conventional lines may restrict opportunities for innovation. While the movement of people from universities to companies is not uncommon, the opposite flow is more constrained.[19] More fellowships are needed that straddle the boundary between universities and industry. Flexible fellowships will be instrumental in diversifying the scientific workforce to include more women and those with industry experience. **We recommend that fellowships are made more flexible and transferable between institutions.**

11 1994 Group (2009). *Survey on the Impact of the Roberts' Fund at 1994 Group institutions. A summary of findings from a research project commissioned by the 1994 Group's Research & Enterprise Policy Group.* 1994 Group: London, UK.

12 Vitae (2009). *Careers in Research Online Survey (CROS) 2009. Analysis of aggregated results.* Careers Research and Advisory Centre: Cambridge, UK.

13 Particularly those run by The Career Development Organisation (CRAC). See: www.crac.org.uk

14 HM Treasury (2002). *SET for success. The supply of people with science, technology, engineering and mathematics skills. The report of Sir Gareth Roberts' Review.* HM Treasury: London, UK; CST (2007). *Pathways to the future: the early career researchers in the UK.* Council for Science and Technology: London, UK

15 RCUK Academic Fellowships provide support for up to 5 years, whilst the Royal Society University Research Fellowship scheme provides support for up to 8 years.

16 93% of past Royal Society University Research Fellows (URFs) are still in a research-based career, with 36% of these being University professors.

17 Evidence provided by RCUK. In 2008/2009, 7% of the EPSRC's budget was spent on fellowships. In 2009, 5% of the Science and Technology Facilities Council's budget, and 4% of the Natural Environment Research Council's budget were spent on fellowships.

18 15% of Royal Society URFs have taken their awards to a new organisation between 2006 and 2008.

19 For example, only a third of Royal Society Industry Fellowships are taken up by scientists in industry.

Recommendation 3

Strengthen Government's use of science

PART 3

Recommendations

Actions

- **Review strategic science spending by Government departments**
- **Expand the Small Business Research Initiative to support innovative procurement**
- **Provide Departmental Chief Scientific Advisers with greater resources**
- **Appoint a Chief Scientific Adviser to HM Treasury**

Public policy is increasingly dependent on complex science. Two decades of controversies over bovine spongiform encephalopathy (BSE), genetic modification, foot and mouth disease, stem cell research, drug classification and countless other issues have tested the often uneasy relationship between science, policy and the wider public. The everyday business of government, whether approving new medicines, controlling environmental pollutants or regulating financial markets, also demands constant input from scientists and other experts.

Red chalk drawing of sand, Antoni Van Leeuwenhoek, 1704 © The Royal Society

Departmental spending on science

As science in universities has flourished, there has been a relative decline in Government's spending on science outside the ring-fence, particularly defence R&D (see Figure 3.3.1). The money that Government departments spend on research is at constant risk of being raided as policy makers are confronted with short-term priorities. This undermines Government's strategic objectives, hinders science-based innovation and puts undue pressure on Research Council science to deliver strategic policy goals.[2]

Strategic research funded through Government departments can be world class in its own right (see Case study 3.3.2) but, more importantly, it underpins innovation in other areas, through instrumentation, monitoring, standardisation and regulation. A substantial proportion of Government's R&D is carried out by Public Sector Research Establishments (PSREs). PSREs vary in form, size and remit, covering issues from fish to forestry, metrology to meteorology. The last two decades have seen PSREs morph from a network of national labs to a diverse mix of public and private bodies. There is a lack of coordination, communication and clarity about how the work of PSREs fits with the needs of Government and the science base.[3]

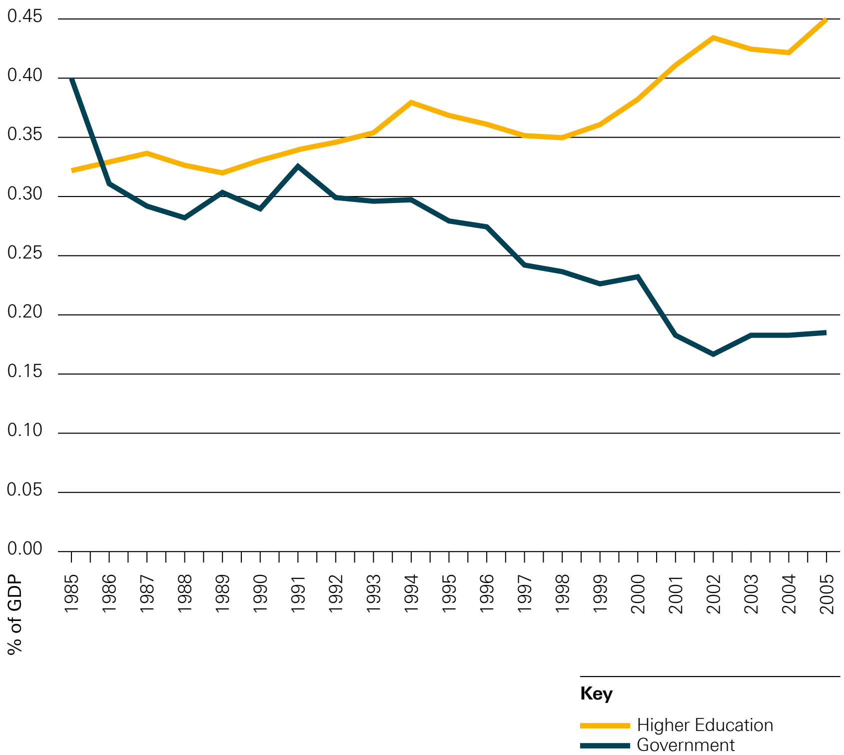
Government needs to ensure that the research it commissions meets its needs and provides value for money. Where research is of strategic importance, it must be protected from everyday budgetary pressures. The Sainsbury Review strengthened existing checks on departmental R&D, demanding discussions with the Government's Chief Scientific Adviser before cuts take place.[4] These reforms now need to be strengthened. **We recommend that strategic science spending by Government departments should urgently be the subject of an independent review.**

The total Government procurement budget dwarfs spending on science by either the public or private sector. If just a fraction of the £220 billion spent each year could be directed towards innovative products and services, it would produce long-term efficiency savings and stimulate the supply of innovative products, services and R&D.[5] Government has signalled its intent to transform public procurement[6] and these efforts should be intensified. **The Small Business Research Initiative, which provides grants for innovative small companies, is working well under the direction of the Technology Strategy Board (TSB), and should be rapidly expanded.**

Making use of scientific advice

Shortly after his election, President Obama argued that 'promoting science isn't just about providing resources – it's about protecting free and open inquiry... It's about listening to what our scientists have to say, even when it's inconvenient – especially when it's inconvenient.'[7] As illustrated by the recent controversy surrounding Professor David Nutt and the Advisory Council on the Misuse of Drugs (ACMD), the relationship between policy makers and their scientific advisors can be fraught.

Figure 3.3.1 **Public Expenditure on Research and Development as a percentage of GDP by sector, 1985-2007**[1]



1 Source: Department for Business, Innovation and Skills (2009). *SET Statistics. Science, Engineering and Technology Indicators*

2 House of Commons Science and Technology Select Committee (2000). *Government Expenditure on Research and Development: The Forward Look.* Fifth Report, Session 1999/2000. The Stationary Office: London, UK.

3 Royal Society (2010). *The Public Sector Research Establishments.* The Royal Society: London. To be published later in 2010; for Government's own analysis, see *PSREs and the Science Base: A Policy For Sustainable Trading And Joint Strategic Investment In PSRE Infrastructure, Final Report of the Research Council Institute and Public Sector Research Establishment Sustainability Study (RIPSS)* Steering Group.

4 Lord Sainsbury of Turville (2007). *The Race to the Top: a Review of Government's Science and Innovation Policies.* The Stationery Office: London, UK.

5 Lord Drayson (2009). *Foundation for Science and Technology lecture.* Royal Society: London, UK. 04 February 2009; CBI (2006). *Innovation and public procurement: a new approach to stimulating innovation.* CBI: London, UK. The total figure is taken from the Policy Through Procurement Action plan, 2010, available online at: http://www.ogc.gov.uk/documents/PtP_Action_Plan.pdf

6 HM Treasury (2007). *Transforming Government Procurement.* HM Treasury: London, UK.

7 Science Team Rollout Radio Address (2008). Remarks of then President-Elect Barack Obama. Friday, December 17, 2008.

Case study 3.3.2 **The Met Office**

The Met Office was created in 1854, at a time when passenger ships and the British Navy were threatened by the unpredictability of storms. Its weather forecasts have become part of British life, making it one of the best-known Public Sector Research Establishments. It is less widely recognised as a centre of scientific excellence. But this has been the hallmark of its continuing success in weather forecasting since the 1970s.

The Met Office Hadley Centre, founded in 1990, has become a world leader in climate science, playing a major role in each of the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports and the Stern Review on the Economics of Climate Change.[8] The everyday operational responsibilities of the Met office keep its science highly relevant.

All of this demands state-of the-art supercomputing. By 2011, Met Office computers will deliver close to 1 trillion calculations per second, and will enable more detailed forecasts of extreme weather and improved predictions of regional climate change.

Such predictions are already being used by business, particularly in insurance. A growing number of national meteorological services around the world, including Australia, South Korea and India, rely on Met Office models to deliver their weather forecasts.

The Met Office is owned and managed by the Ministry of Defence (MoD), but is not solely a Government body and became a Trading Fund in 1996. Government has continued to be its main customer and funder but in 2008, one-sixth of its £176.5 million budget came from commercial services.

Long term public investment in Met Office research has given the UK an enviable national capability in weather forecasting and climate prediction. But the vulnerability of PSREs was recently exposed when the MoD announced cuts of £4.3 million to the Met Office's climate research funding. The Met Office is now in discussions with Government about finding a long term and sustainable future for its vital research and services.

Figure from Newton's 'Optiks', Book 1, part 2, Plate IV, figure 16.

It is impossible to put a figure on the value of good scientific advice. But the costs of past failures are clear. The BSE crisis had, by 2000, cost the Government £3.7 billion.[9] The costs to long-term public trust were far higher. Described by some as the 'worst failure of UK public policy since the Suez Crisis of 1956'[10], BSE exposed a fracture in the relationship between science and government.

There has since been great progress in the way that scientific advice is sought and used in policy-making. The Government's 'Guidelines on Scientific Advice' advocate taking advice from a wide range of experts – scientists, social scientists, engineers, clinicians and others – and openly acknowledge scientific uncertainty in policymaking.[11] These guidelines are currently being revised and strengthened, in part as a response to the recent problems with the ACMD.

The appointment of Chief Scientific Advisers to most Government departments has strengthened Government's links with the scientific community and led to an improvement in the use of science across Whitehall.[12] But the roles and policy influence of CSAs vary from department to department. Maximising the value of these senior scientists at the heart of government necessitates equipping them with the resources to make a difference. **We recommend that departmental CSAs are given greater resources to inform and provide constructive challenge to policy makers.**

Policies for science and innovation themselves need a more solid foundation in evidence and empirical data. The US Government has led efforts in this area through its 'Science of Science and Innovation Policy'[13] research programme. To reinforce the quality of its own decision making, the UK should invest in a parallel programme, building on the work of the UK Innovation Research Centre and the EPSRC/ESRC Advanced Institute of Management initiative.

We also recommend that HM Treasury appoints a chief scientific adviser to ensure a scientific voice at the heart of economic policy, able to inform strategies for growth and investment. And we support recent calls for a senior scientific adviser to the Bank of England.[14]

8 Stern N (2007). T*he Economics of Climate Change: The Stern Review.* Cambridge University Press: Cambridge, UK.

9 BSE Inquiry Report (2000). *Volume 10 – Economic Impact and International Trade.*

10 van Zwanenberg P and Millstone E (2005). *BSE: Risk, Science, and Governance,* Oxford University Press: Oxford, UK.

11 HM Government (2005). *Guidelines On Scientific Analysis in Policy Making.* Cabinet Office: London, UK

12 House of Commons Innovation, Universities, Science and Skills Committee (2009). *Putting Science and Engineering at the Heart of Government Policy. Eighth Report of Session 2008-09. Volume I.* The Stationary Office: London, UK.

13 Marburger III J (2005). *Wanted: Better Benchmarks. Science.* **308**. 5725. p1087.

14 See: King D. *The Bank's green future.* Prospect. **166**. 15th December 2009. Available online at: http://www.prospectmagazine.co.uk/2009/12/the-banks-green-future/

Recommendation 4

Reinforce the UK's position as a hub for global science and innovation

PART 3

Recommendations

Actions

- **Extend the geographic reach of the UK Science and Innovation Network**
- **Increase support for mechanisms, such as the Science Bridges scheme, which link UK research groups with partners overseas**
- **Incentivise more of the world's best scientists to remain in, or relocate to, the UK**
- **Improve visa conditions for visiting scientists and researchers to the UK**

If the UK wants to remain a hub for global science, we must connect and collaborate with the best science in the world, wherever it is being conducted. For the UK to remain truly innovative, innovative people must move to and through it. The UK has done well historically, attracting many of the world's best scientists to carry out research here, but policies for science and innovation must keep pace with globalisation if the UK is to continue to compete.

The UK contributes to and benefits from international science

Researchers, funders and policy makers all acknowledge the importance of international collaboration for the UK. Much of this grows from a desire among scientists to collaborate with their best international peers. This needs to be met with a strategic approach from policy makers. Research Councils UK published an international strategy in June 2007.[1] But despite a commitment in the Innovation Nation white paper[2], and in contrast to countries such as Germany and Japan, there is still no coherent UK strategy for international science and innovation.

Policy makers often bemoan stories of science conducted in the UK leading to wealth in other countries through technologies such as fibre-optics, MRI scanners and the World Wide Web. But just as the UK's world class science can produce economic opportunities in other countries, so the UK can realise the innovation potential of international science. Innovation is not confined by geography. Ideas can travel and be adopted by anyone at any time. The UK needs to maximise its economic chances by increasing its 'absorptive capacity' – the ability to access, adopt, adapt, exploit and diffuse the benefits of both original research and knowledge translation.[3]

Promoting UK science worldwide

The UK's Science and Innovation Network (SIN), which operates in 25 countries, demonstrates the value that can be created through interactions between science and diplomacy, particularly in targeted areas such as low-carbon technologies. Networking and Focal Point schemes with India, China, South Africa and South Korea have brokered long term collaborations for UK science. **We recommend that the geographic reach of SIN should now be extended, particularly across the Middle East, Africa and South America.** SIN should continue to work closely with the Research Councils, the British Council, UKTI, DFID, other Government departments, and other partners, pooling resources where appropriate, with the common aim of promoting UK science internationally.

Supporting research networks

Scientific excellence can be judged by its international impact. Evidence suggests that the UK competes most effectively by collaborating. In 2007, 47% of UK publications had a non-UK co-author, and these papers had a higher impact factor than those with sole UK authorship.[4]

The most pressing problems facing our planet demand research solutions that extend beyond the capabilities of single countries. The UK should support strategic research directed at global challenges, in collaboration with international partners. The 'Science Bridges'[5] and similar initiatives are generating strategic links between UK and international universities, taking ideas from the lab bench through to market. Such schemes, which support both mobility and research, are not a luxury; they are a key strand of any strategy to ensure that the UK remains central to flows of science and innovation around the world. UK funders should increase their support for joint international research activities. **In particular, we recommend that the Research Councils and TSB extend the Science Bridges scheme to include other international partners.**

Supporting international people

The UK's universities are truly cosmopolitan, attracting students and staff from around the world. The market for international students brings substantial income to universities (£4 billion per year in fees, or 8 percent of total income,[6] as well as £2.3 billion in off-campus expenditure[7]), but their potential value is much greater than the fees they pay. The UK needs to get smarter about making the most of its international researchers and their networks.

Fears in the 1960s of a steady 'brain drain' from the UK to the US may have passed, but the world's best scientists now have more options around the world. The UK must remain a first choice destination. Its world class science base is a significant asset in this regard. But leading scientists should also be incentivised, through top up grants or specific funds, to remain in, or relocate to, the UK with their research groups.

Prestigious schemes exist in the UK, but the number of awards is small and competition is fierce. Newton International Fellowships bring 50 early-career researchers across the sciences, engineering, humanities and social sciences to the UK each year (see Figure 3.4.1), building links between the UK

1 Research Councils UK (2007). *RCUK International Strategy.* Research Councils UK: Swindon, UK.

2 DIUS (2008). *Innovation Nation.* Department for Innovation Universities and Skills: London, UK.

3 NESTA (2008). *Innovation by adoption, Measuring and mapping absorptive capacity in UK nations and regions.* National Endowment for Science, Technology and the Arts: London, UK.

4 Evidence Ltd (2009). *International comparative performance of the UK research base.* Department for Business, Innovation and Skills: London, UK.

5 Science Bridges have funded a range of initiatives, including a University of Lancaster partnership with Chinese laboratories on sustainable water management, the BioPharm2020 project between the University of Nottingham and leading Indian institutes in Kanpur and Bangalore, and a collaboration between the SETsquared partnership in the UK (made up of the Universities of Bath, Bristol, Southampton and Surrey) and the University of California to develop further their expertise in commercialisation and spinning out their research.

6 HESA (2009). *Students in Higher Education Institutions 2007/08.* Higher Education Statistics Agency: Cheltenham, UK.

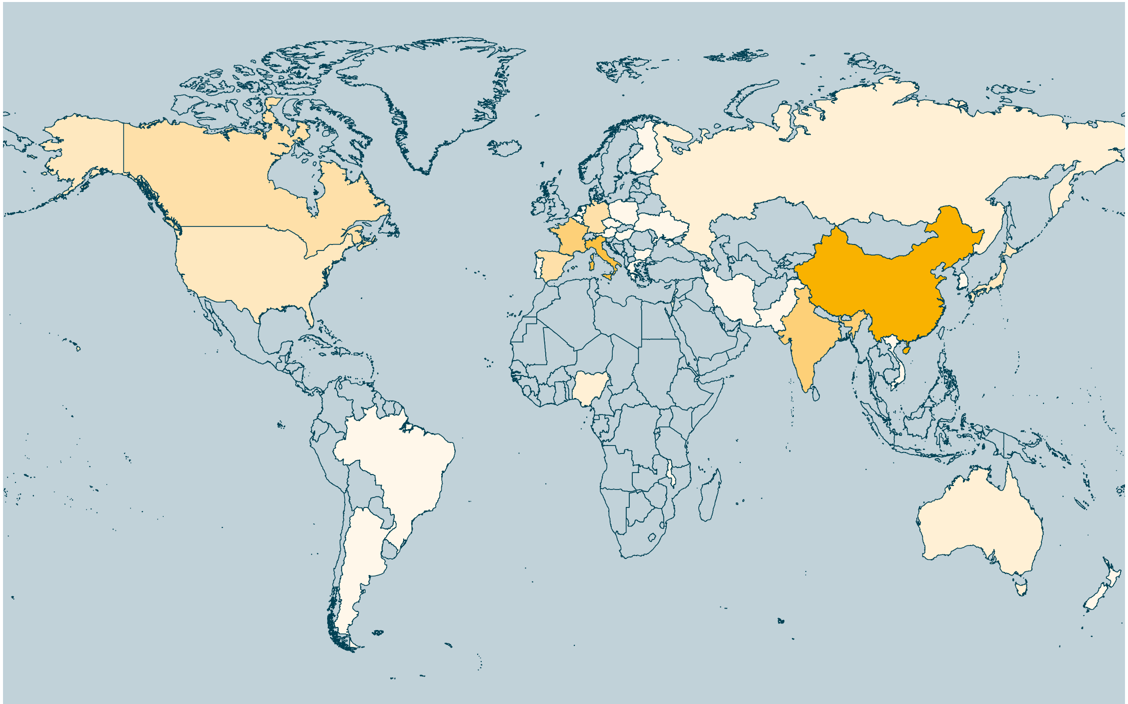
7 Universities UK (2009). *The impact of universities on the UK economy.* Universities UK: London, UK.

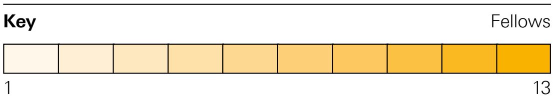
and the future global leaders of science. The Royal Society's Wolfson Research Merit Awards (WRMA) and Research Professorships target the very best scientists and provide support for them to conduct their research in the UK. There are currently 168 WRMA holders, and 21 Royal Society Research Professors, of whom more than 50 have been attracted to the UK from overseas.

As funding allows, we recommend that initiatives to incentivise excellent individuals to remain in or relocate to the UK should be scaled up. In particular, the number of Newton Fellowship awards should be doubled, and the commitment to support alumni should be maintained.

UK researchers have long complained of the difficulties that their overseas colleagues face in navigating UK visa regulations. The recently introduced points based migration system should, in theory, make it easier for highly qualified researchers to access the UK. However, researchers are still finding it difficult to enter or remain in the UK, even when taking part in official schemes. **We recommend that the Home Office should issue guidelines to ensure that the visa applications of visiting researchers are dealt with swiftly and with reference to the support of hosting UK institutions.** It is essential for the future of the UK's science base that the doors remain open for the world's scientists to visit our universities and research institutes for days, weeks or years at a time.

Fig 3.4.1 **Nationality of incoming Newton International Fellows to the UK, 2008-2009**





Recommendation 5

Better align science and innovation with global challenges

PART 3

Recommendations

Actions

- **Create strong global challenge research programmes, led by RCUK, to align scientific, commercial and public interests**
- **Reform research funding and assessment to support and reward interdisciplinary research**
- **Use public and stakeholder dialogue to help identify and shape these challenges**
- **Ringfence departmental contributions to priority research areas**

Climate change, food security, biodiversity, poverty and population growth are just some of the environmental and social pressures that will shape the coming century (see Figure 3.5.1). They will alter how we live, the balance of risks that we face, and the ways that we govern a more interdependent world. The danger is that a combination of these factors will produce what the UK Government's Chief Scientific Adviser describes as a mid-century 'perfect storm'.[2]

Tackling these challenges will require the best available science: to measure and predict impacts; to identify solutions; and to evaluate pathways for adaptation. No one country or scientific discipline will be able to offer complete solutions.[3] Instead, a challenge-led approach will increasingly be required to deliver innovative, global responses. This should mobilise the research community, bring together disparate research areas and harness public and private sector support. Such an approach should be designed to satisfy the social demand for strategically important science without stifling innovation.

Top-down vs. bottom-up

There can be tensions between basic science and strategically important science. The former is unpredictable and serendipitous, demanding a bottom-up funding system led by researchers. The latter requires funders to identify priorities and allocate funding from the top down. Realising the potential of science to address global challenges requires a new approach to science policy. Policies that pick winners and prescribe solutions are rarely successful.[4] But there is a clear role for policy in articulating global challenges and helping to connect these to scientific solutions more rapidly.[5]

Rather than pushing researchers towards certain sorts of science and asking them to define and deliver short-term impacts, well-defined global challenges can pull science towards shared goals. Identifying problems protects the space for free enquiry by asking the scientific community to identify solutions that meet societal needs.[6] At a 2009 conference in Lund, 350 researchers and policy makers criticised the European Commission's funding of research according to fixed themes, and advocated a new emphasis on 'grand challenges'.[7] In the US, President Obama has promised to 'harness science and technology to address the grand challenges of the 21st century'.[8]

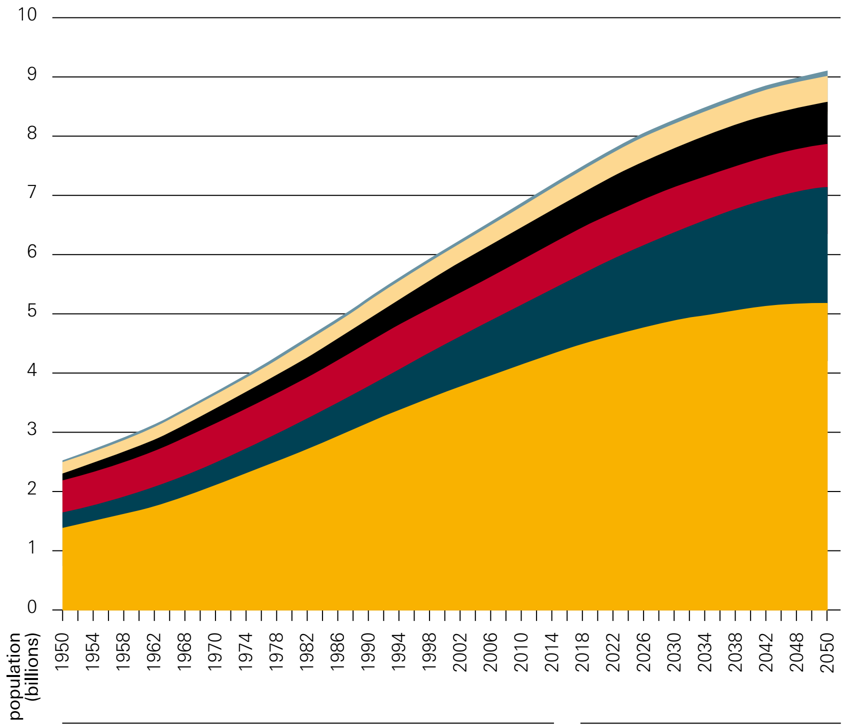
Strengthening RCUK

In the UK, individual Research Councils have begun to experiment with different mechanisms for mobilising the research community through challenges.[9] These have tended to focus on particular scientific or engineering problems and have been effective at initiating research in new areas. A global challenge approach must be longer-term, and reach beyond individual institutions and disciplines.

Research Councils UK currently oversees a number of cross-cutting priority themes that go some way towards a global challenges model: Global Security in a Changing World, Living with Environmental Change, Lifelong Health and Wellbeing, Energy, Digital Economy, Nanoscience and, most recently, Food Security. With the exception of Nanoscience, these themes are problem-driven and cut across individual Research Councils. They have been useful in bringing the Research Councils together and strengthening the UK's position at the frontier of certain disciplines.

Solutions to global challenges may come from different parts of the research community, from social innovation or from combined action on many fronts. Solutions to the challenges of food security, for example (see Case study 3.5.2), will depend on combinations of science, engineering, social innovation, markets, infrastructure, political action and good governance. And challenges such as global education and criminal justice will lean heavily on the social sciences for explanation and solution. Challenge-led research must bring together disciplines and mix basic science with near-market innovation. Despite moves to encourage collaboration, the way that research is funded, assessed and conducted remain highly disciplinary. Current cross-council themes are each led by one council, which may impede genuine collaboration.

Figure 3.5.1 **World population growth, 1950-2050**[1]



Current UN estimates of population growth predict a global population of over 9 billion by 2050, exacerbating pressures on food, water and energy resources.

1 Source of statistics: United Nations Department of Economic and Social Affairs, Population Division (2009). *World Population Prospects.* United Nations: New York NY, USA.

2 Beddington J (2009). *Food, Energy, Water And The Climate: A Perfect Storm Of Global Events?* Department for Innovation, Universities and Skills: London, UK.

3 Royal Society (2010). *New Frontiers in Science Diplomacy. Navigating the changing balance of power.* Royal Society: London, UK.

4 European Commission (2009). *The Role of Community Research Policy in the Knowledge-Based Economy: Report of an Expert Group to the European Commission.* European Commission: Brussels, Belgium.

5 Samarasekera I (2009). *Universities need a new social contract.* Nature, **462**, pp 160-161; see also Anniversary address by the President of the Royal Society (2009). Royal Society: London, UK. November 2009.

6 Gassler H, Polt W and Rammer C (2007). *Priority Setting In Research & Technology Policy – Historical Developments And Recent Trends "Innovation Policies In Europe".* Intereg Working Paper No. 36-2007. Edward Elgar Publishers.

7 The Lund Declaration was the outcome of the 'New Worlds – New Solutions' conference held to discuss the future development of European research.

8 Executive Office of The President, National Economic Council, Office of Science and Technology Policy (2009). *A Strategy for American Innovation: Driving Towards Sustainable Growth and Quality Jobs.* Executive Office of the President of the United States: Washington DC, USA.

9 See, for example, EPSRC's four new Chemical Sciences and Engineering Grand Challenges announced in Summer 2009: www.epsrc.ac.uk/ResearchFunding/Programmes/PhysSci/RC/gcreport.htm

PART 3

Recommendations

Case Study 3.5.2
The next Green Revolution[10]

200 years ago, Thomas Malthus predicted that growth in population would lead to mass starvation as food supplies grew scarce. But in the second half of the twentieth century, rapid increases in crop yields outpaced a doubling of the global population. The technological and agricultural changes that made this possible have come to be known as the 'Green Revolution.' New varieties of wheat were bred with two major genetic improvements – dwarfing (shorter stems) and resistance to stem rust. The genetic potential of these new crops was realised through changes in practice and greater use of mineral fertilizer and water. Dwarfing allowed for the increases in yield provided by nitrogen fertilisers without the crops lodging (falling over). Similar changes were made to rice varieties in Asia. China, in particular, saw a five-fold increase in per capita yield over the second half of the 20th Century.

The Green Revolution also led to a profound transformation in the way that research was organised. Research institutes around the world came together under the umbrella of the Consultative Group on International Agricultural Research (CGIAR), which continues to catalyse innovation and implement scientific advances for agriculture across the world.

But the achievements of the Green Revolution have come at some cost. Increases in yield have been accompanied by sharp increases in fertiliser, pesticide and water use. And some countries have benefited more than others. The complexities of African agricultural landscapes, with mixed crops, and poor access to credit, markets, seeds and fertilisers, did not suit Green Revolution crop varieties. In Africa, yields have remained relatively static.[11]

These successes and limitations of the Green Revolution have led to many calls for renewed investment and collaboration directed at step changes in agricultural productivity, albeit with greater consideration of side effects.[12] In 2009, the Royal Society called for the UK's research funders to come together in a sustained 'grand challenge' approach to global agricultural research.[13] This would address the need for science, technology, social science and improved governance in tackling the problems of global food insecurity.

Record of the founding of the Royal Society and first meeting on 28 Nov 1660 © The Royal Society

Global challenge programmes should be created and managed at an overarching level, with a stronger role for Research Councils UK. Systems of research funding and assessment should be reformed to support and reward interdisciplinary research.

Identifying the challenges

The process of identifying global challenges for science and society should be a key part of renewing science's 'social contract', enabling public engagement and inspiring science education. **The identification and articulation of global challenges should include public and stakeholder dialogue.** The Engineering and Physical Sciences Research Council recently pioneered such an approach to help inform its nanotechnology strategy.[14] From the scientific end, foresight exercises will be vital in turning grand aspirations into solvable questions. The current UK Government Foresight project on food and farming, for example, will help bring food security problems and solutions closer together.[15]

Global efforts for global challenges

A global challenge approach will only be successful if it works within an international framework.[16] Collaboration between researchers and research teams will need to be complemented by strategic network building and diplomacy.[17] The Intergovernmental Panel on Climate Change is the most prominent example of coordinated activity to address a global challenge, drawing on the best international research. Global challenges can serve as a magnet for global collaboration. Here, the UK has an opportunity for global leadership. National programmes should be linked and co-ordinated with international organisations (for example, the Gates Foundation).

By better articulating the challenges facing us, researchers and funders can strengthen connections between institutions and increase the chances of galvanising public and private sector commitments. Aligning funding, research capabilities and expertise means that efforts can achieve a critical mass that governments alone would find impossible. By developing a shared approach to these challenges, Research Councils, Government departments, the TSB and businesses can accelerate the development of responses to large-scale social, economic and environmental challenges. But contributions to joined-up research programmes from outside the Research Councils are at greatest risk from budget cuts. **We recommend that Government departmental contributions to collaborative research programmes should be protected for the duration of those programmes.**

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10 Royal Society (2009). *Reaping the Benefits: Science and the sustainable intensification of global agriculture.* Royal Society: London, UK.

11 Paarlberg R (2006). *Are genetically modified (GM) crops a commercial risk for Africa?* International Journal of Technology and Globalisation **2**, pp 81-92.

12 Conway G (1997). *The Doubly Green Revolution: Food for All in the Twenty-First Century.* Penguin Books Ltd; Swaminathan M (2000). *An evergreen revolution.* Biologist: London **47(2)**, pp 85-9. April 2000; Sanchez P, Denning G, and Nziguheba G (2009). *The African Green Revolution moves forward.* Food Security **1**, pp 37-44.

13 Royal Society (2009). *Reaping the Benefits: Science and the sustainable intensification of global agriculture.* Royal Society: London, UK.

14 See: BMRB (2008). *Nanotechnology for healthcare, Report for Engineering and Physical Sciences Research Council.* BMRB: London, UK; and Jones R (2009). *Public Engagement and Nanotechnology – The UK experience,* in *The Road Ahead: Public Dialogue on Science and Technology.* Sciencewise

15 See www.foresight.gov.uk/OurWork/ActiveProjects/FoodandFarmingFutures/

16 The European Research Area proposal promises 30% of funding across Europe to Grand Challenge projects. There are also similar programmes coming out of the G8 Research Council and NGOs such as The Gates Foundation.

17 Leshner A and Turekian V (2009). *Harmonizing Global Science.* Science **326**, 5959, p. 1459

Recommendation 6

Revitalise science and mathematics education

PART 3

Recommendations

Actions

- **Provide incentives to recruit, retain and attract teachers back to science subjects**
- **Commit to increasing the numbers of primary teachers with science expertise**
- **Establish new expert groups to advise on the development of science and mathematics curricula and qualifications**

The success of policies for the future of science and innovation will rest ultimately on the education of young people. Whether they are destined to become professional scientists or scientifically-literate citizens, the natural curiosity of young people should be encouraged through science education. A world class science and mathematics education system needs qualified specialist teachers who are committed, well-trained and well-supported. Science and mathematics education have specific requirements, but have suffered from decades of buffeting by political interference and piecemeal reform.

Recruitment and retention of subject specialists

In science and mathematics education, we can see clearly the limitations of a one-size-fits-all approach. Teaching needs to be tailored to fit the unique characteristics of each subject, and subject specialists are crucial to this. The Royal Society, in its first 'state of the nation' report on *The UK's science and mathematics teaching workforce*, noted that, 'Teachers are generally the greatest influence on a young person's personal and intellectual development other than parents or guardians. In science and mathematics… the role of the teacher becomes even more critical.'[1]

Evidence from scientists suggests that inspirational teachers are a key factor in encouraging young people to enter scientific careers.[2] In subjects such as physics and chemistry, the under-supply of high-quality teachers has become a chronic problem. A number of new mechanisms have sought to train, recruit, retain and attract science teachers back to teaching. But it is impossible to ignore the fact that over the last decade the Government has consistently failed to meet its recruitment targets for secondary science and mathematics teachers, compounding the problem further (see Figure 3.6.1).

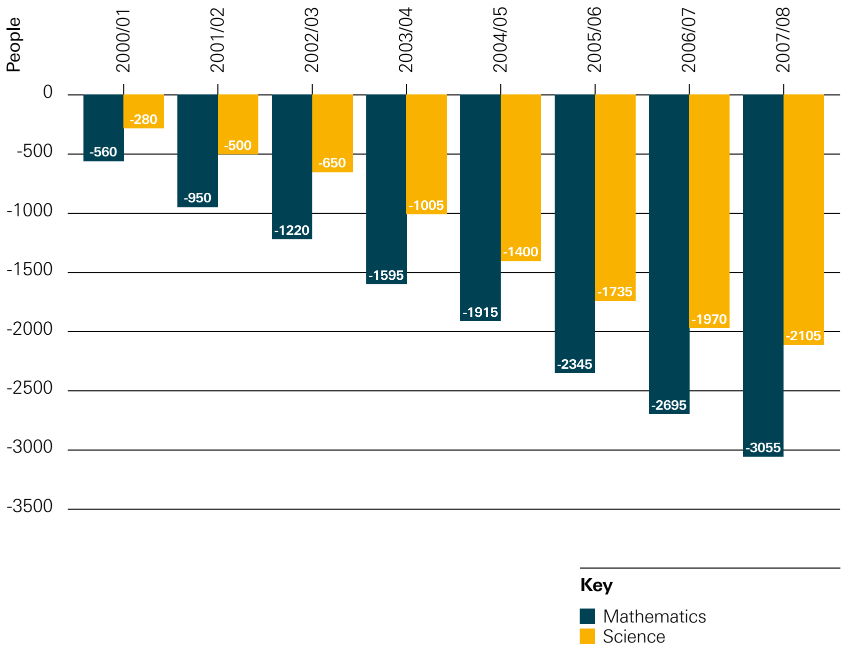
We support the recent recommendation of the Science and Learning Expert Group that Government should focus on boosting participation through non-standard routes such as 'Transition to Teaching' and 'Teach First'.[4] Resources should be made available to ensure that no well-qualified applicant is turned away from science and mathematics teacher training.[5]

Robert Hooke's sketch on refraction of ice, 1662 © The Royal Society

2009 was the first year in more than a decade when these targets were met and this can be largely attributed to rising unemployment caused by the recession. Poor teacher retention and a high rate of retirement exacerbate the problem.[6] In order to tackle this problem successfully, there needs to be long-term commitment to well-supported measures that maximise recruitment.[7] At secondary level and beyond, there is a need to ensure that there are enough teachers with appropriate subject knowledge. Head teachers and their governing bodies have a significant role to play by facilitating subject-specific continuing professional development.

The primary phase is more complicated. Here teachers need stronger early years pedagogical skills in addition to subject knowledge. In June 2008, in response to recommendations from the Williams Review, the Secretary of State for Children, Schools and Families (DCSF) allocated £187m over ten years to pay for 13,000 mathematics specialists, aiming for every English primary school to have access to a 'maths champion' who would also mentor and coach colleagues. While this programme is still in its infancy, there is a case for an equivalent policy which would increase the numbers of primary teachers with science expertise. This would also bolster the effectiveness of teacher-based assessment in primary science.[8]

Figure 3.6.1 **Cumulative shortfall in meeting science and mathematics recruitment targets, 2000/1-2007/8**[3]



1 Royal Society (2007). *The UK's science and mathematics teaching workforce. A 'State of the nation' report.* Royal Society: London, UK.

2 Royal Society (2004). *Taking a leading role – scientists survey.* Royal Society: London, UK.

3 Adapted from: Royal Society (2007). *The UK's science and mathematics teaching workforce. A 'State of the nation' report.* Chapter 5. Royal Society: London, UK.

4 See: www.tda.gov.uk/Recruit/adviceandevents/transition_to_teaching.aspx and www.teachfirst.org.uk/.

5 Science and Learning Expert Group (2010). *Science and Mathematics Secondary Education for the 21st Century.* Department for Business, Innovation and Skills: London, UK, and Department for Children, Schools and Families: London, UK.

6 See: TDA (2009). *'Bumper year' for numbers of new trainee teachers helps drive up quality.* Training and Development Agency for Schools: Manchester, UK; and Barmby B and Coe R (2004). *Evaluation of the repayment of teachers' loans scheme.* Department for Education and Skills: London, UK.

7 Royal Society (2007). *The UK's science and mathematics teaching workforce. A 'State of the nation' report.* Chapter 5. Royal Society: London, UK

8 DCSF (2008), *Independent Review of Mathematics Teaching in Early Years Settings and Primary Schools Final Report – Sir Peter Williams.* Department for Children, Schools and Families: London, UK. See also: the Mathematics Specialist Teacher (MaST) programme, available online at: www.ncetm.org.uk/resources/21133. The Royal Society's forthcoming 'state of the nation' report on 5-14 science and mathematics education will be highlighting the key role of primary science and mathematics specialist teachers.

We recommend that Government provides more effective long-term incentives to recruit, retain and attract teachers back to science subjects. Building on the available evidence, Government needs a clear policy to increase the number of primary teachers with science expertise.

Curiosity, the curriculum and assessment

Understanding science involves much more than just the learning of facts.[9] Science education is complex, and must serve two objectives. First, it must aim to increase the scientific and mathematical literacy of young people in general. Second, it must stretch and challenge those with the potential to become tomorrow's scientists. The introduction of 'How science works' and 'Functional mathematics' to the curriculum has increased the emphasis on the first objective.[10] It remains to be seen what impact this will have on those students with the potential to enter scientific careers.

There has been a statutory national curriculum for 5-16 year olds in maintained schools in England, Wales and Northern Ireland since 1989 and a similar curriculum is starting to emerge in Scotland. A national curriculum identifies and mandates a minimum educational entitlement, meaning that learners in different places have common core knowledge and skills. The importance of mathematics as a subject in its own right is now fully recognised, as is the need for its inclusion within science, especially at post-16 level.[11]

But the approach adopted in the national curriculum risks dividing science and mathematics into pieces, losing the connections necessary for a deep understanding of these subjects. The current curriculum also discourages hands-on engagement with practical science.[12] Assessment regimes can restrict how the curriculum is taught, stifling innovation and creative teaching.[13] League tables may take precedence over the educational needs of students. 'Teaching to the test' can work against more constructive and formative assessment.[14]

Curriculum and assessment are inextricably linked and assessment must be rigorous and thorough. Tests must assess what matters, not only what it is easy to assess. An appropriate and authoritative assessment process must have experts who are trained in assessment methodology and who are, or have been, practising teachers. Curriculum and assessment should be designed to meet the needs of a range of students, providing scientific literacy in general while stretching and challenging those likely to continue in science.

It is essential that there is a seamless progression for students through different stages of education. Review of the education system must be holistic, long term and systematic. Timescales must allow for effective development, trialling and implementation phases. This demands a new approach which should be based on a close working partnership between subject specialists and those who have pedagogical expertise.

We recommend that Government establishes new expert groups to advise policy makers on the development of curricula and qualifications, to ensure that school science and mathematics education meet the future needs of the UK.

The subject specialist groups should include representatives drawn from schools, HEIs, professional and learned societies and employers, and should work alongside regulatory bodies to advise policy makers. We strongly support the Science and Learning Expert Group recommendations that echo this point. UK regulators should explain in their annual reports how they engage with their subject communities to ensure confidence in qualifications.[15]

Map/plan from Francis Vernon's notebook on the Parthenon, 1675-1676

9 Bransford J, Brown A, and Cocking R (1999). *'How people learn' Brain, Mind, Experience, and School.* National Academy Press, Washington DC, USA.

10 See: www.qcda.gov.uk/9437.aspx and curriculum.qcda.gov.uk/key-stages-3-and-4/skills/functionalskills/index.aspx for descriptions.

11 ACME (2009). *The Mathematics Education Landscape in 2009.* Advisory Committee on Mathematics Education: London, UK; SCORE (2008). *GCSE Science 2008 Recommendations Report.* Science Community Representing Education: London, UK; and SCORE (2009). *Science diploma: recommendations.* Science Community Representing Education: London, UK.

12 SCORE (2008). Practical work in science: A report and proposal for a strategic framework. Science Community Representing Education: London, UK.

13 See for example Ofsted's response to the Third Report from the Children, Schools and Families Committee, Session 2007-08 on Testing and Assessment, available online at: www.publications.parliament.uk/pa/cm200708/cmselect/cmchilsch/1003/100305.htm

14 Royal Society (2004). *Statement on the assessment of science learning 14-19.* Royal Society: London, UK.

15 Science and Learning Expert Group (2010). *Science and Mathematics Secondary Education for the 21st Century.* Department for Business, Innovation and Skills: London, UK, and Department for Children, Schools and Families: London, UK.

Glossary of acronyms

ACMD Advisory Council on the Misuse of Drugs

AHRC Arts and Humanities Research Council

BBSRC Biotechnology and Biological Sciences Research Council

BIS Department of Business, Innovation and Skills (formerly DIUS: Department for Innovation, Universities and Skills)

DECC Department of Energy & Climate Change

DEFRA Department of Environment, Food & Rural Affairs

EPSRC Engineering and Physical Sciences Research Council

ERC European Research Council

ESRC Economic and Social Research Council

FP Framework Programme

GDP Gross domestic product – a measure of total economic activity

GERD Gross expenditure on research and development

GVA Gross Value-Added: the contribution to the economy of each individual producer, industry or sector in the UK (GDP minus taxes plus subsidies on products)

HEFCE Higher Education Funding Council for England

HEI Higher education institution

HESA Higher Education Statistics Agency

IPCC Intergovernmental Panel on Climate Change

MRC Medical Research Council

NERC Natural Environment Research Council

OECD Organisation for Economic Co-operation and Development

R&D Research and development

RAE Research Assessment Exercise: soon to be replaced by the Research Excellence Framework

RCUK Research Councils UK: a partnership of the UK's seven research councils

SIN Science and Innovation Network

SPRU Science and Technology Policy Research at the University of Sussex

STEM Science, technology, engineering and mathematics

STFC Science and Technology Facilities Council

TSB Technology Strategy Board

Conduct of the study

Rationale and objective

The Royal Society established an Advisory Group for this project of experts from academia, business and science policy, chaired by Sir Martin Taylor FRS. The aims of the study as outlined in the Terms of Reference were to contribute to the development of a strategy for the future of the UK's science and innovation base over the next 20-25 years. The primary focus was on the UK, but the study also considered the international context for science and innovation activities. Its specific goals were:

- To identify and assess the different forms of value (economic, social, intellectual and cultural) produced by science, technology, engineering and mathematics
- To make recommendations to policy makers and other decision makers as to how this value can be increased for public benefit

The project was launched, under the working title of 'The Fruits of Curiosity' in April 2009.

Collection of evidence

Evidence gathering for the project took place in three ways:

- A formal process, through an initial Call for Views and a more detailed Call for Evidence;
- A series of meetings and discussions with key stakeholders including representatives from the Research Councils and Professor John Beddington, the Government Chief Scientific Adviser;
- Events on specific themes that arose during the course of the study.

Call for Evidence

The Call for Evidence was published on 21 July 2009. We received 44 responses, from individuals, universities, the third sector, learned societies, industry and business. These are listed below.

All non-confidential responses can be viewed on the Royal Society website at: royalsociety.org/The-Fruits-of-Curiosity/

Association of Medical Research Charities
Bangor University
British Academy
British Psychological Society
Dr Gerald Brooks
Dr Kuang-Hsu Chiang
Dr Laurence Cox
Dr David Dent
Dr Martin Dominik
Elsevier
Professor John Fox
Professor David Gann
Geological Society
Dr Amanda Goodall
Dr Ernest Alexander K Heuer
Institute of Education, University of London
Institute of Physics
Institution of Engineering and Technology
Dr Steve Jewson
John Innes Centre
LGC
Dr Jim McQuaid
National Science Learning Centre
New and Renewable Energy Centre
Pfizer
Professor Richard Noss
Professor Andrew J Oswald
Professor Robert Paton
Research Councils UK
The Royal Academy of Engineering
Royal Astronomical Society
Science Museum
Society for the Study of Artificial Intelligence and the Simulation of Behaviour
Professor Harold Thimbleby

UK Computing Research Committee
UK Innovation Research Centre
University of Cambridge
University of Exeter
University of Glasgow
University of Nottingham
University of Sunderland
Vitae/Career Development Organisation (CRAC)
Wellcome Trust
White Rose University Consortium
1994 Group

Newton's drawing of his reflecting telescope, January 1672

Discussions with stakeholders

The Advisory Group and Secretariat held a number of useful discussions with senior stakeholders, during and outside Advisory Group meetings. Advisory Group members gave evidence to related inquiries by the Council for Science and Technology and the House of Lords and House of Commons Science and Technology Committees.

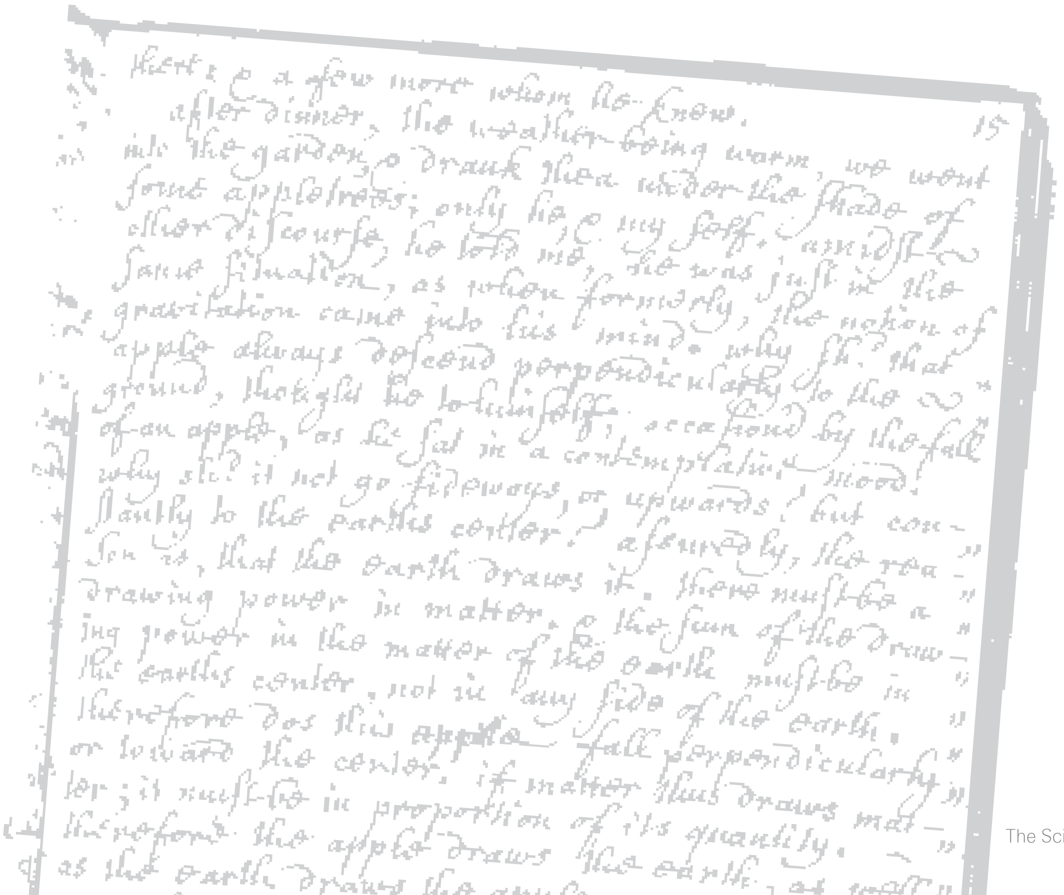
Events

A series of events was held on specific themes:

- *'Building the base: science, stimulus and future sources of wealth creation'*, 1 April 2009, with Adam Afriyie MP
- *'Socrates in the Boardroom: what makes a great academic leader?',* 21 October 2009 with Dr Amanda Goodall and Sir Paul Nurse FRS
- *'Science on tap? – Recognising and rewarding the policy impact of research',* 22 October 2009 with Professor John Beddington FRS, David Sweeney (HEFCE) and Nicola Dandridge (Universities UK).
- *'What science does government need? The future for the UK's public sector research establishments',* 24 November 2009. Speakers included: Professor Brian Collins (BIS), Dr Brian Bowsher (National Physical Laboratory), Professor Julia Slingo (The Met Office).
- *'The public nature of science – Why and how should governments fund basic research?'* 1 December 2009 with Professor Helga Nowotny and Professor Richard Jones FRS.

Future publications

To reflect the more detailed evidence gathered throughout this study, we will be publishing a series of additional working papers as follow-ups to *The Scientific Century* report. These will include papers on the Public Sector Research Establishments, the findings of a series of focus groups with recent PhD graduates, and an assessment of the innovation ecosystem.



Extract from William Stukeley's 'Life of Isaac Newton' telling the story of the apple and gravity, 1752

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Sketches of eyes/light refraction
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Figure from Newton's 'Optiks',
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