CELEBRATE 350 YEARS

THE ROYAL SOCIETY

The Scientific Century: securing our future prosperity

(Final report of the Fruits of Curiosity inquiry)

Responses to Call for Evidence
Part III

Table of Contents

Introduction 3
Responses to Call for Evidence 4
Dr Martin Dominik 4
New and Renewable Energy Centre (NaREC) 10
National Science Learning Centre 14
Pfizer 17
Research Councils UK 21
Professor Richard Noss 44
Professor Andrew J. Oswald 45
Professor Robert Paton 46

Introduction

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. Please refer to the links on the Royal Society website for a copy of the original Call for Evidence document.

Responses to Call for Evidence

Dr Martin Dominik

Submission to "The Fruits of Curiosity: science, innovation and future sources of wealth"

Inquiry by the Royal Society

Dr Martin Dominik – Royal Society University Research Fellow

6 September 2009

I would like to express my highest appreciation to the Royal Society for launching a study into an issue that will be of greatest importance to the future of our society. I sincerely hope that it will create a substantial echo at the right places and help pushing things in the right direction at a current critical stage.

The challenge we are facing can be summarized in a single sentence: If we want to harvest the fruits of curiosity, and thereby advance our society, we have to foster curiosity.

This not only applies to academia and the wider research sector, but early stages in our education system already play a crucial role. All children are born curious, but the majority lose their curiosity at some age, and one should think about whether something goes fundamentally wrong in our schools. It has become fashionable to teach leaders in business and academia about group motivation and the role of positive incentives, but to what extent are school teachers familiar with such concepts? On asking scientists or non-scientists about the reason for their career choices, one frequently hears about the role of their teachers, be it a fascinating and inspiring one, or the diametral opposite.[1] Care needs to be taken to ensure that our children develop a personality and gain self-confidence.

We will only make efficient use of the nation's creative potential if we encourage creative and critical thinking, and moreover provide the environment for realizing new ideas. Today's dreams might well turn into tomorrow's reality, or they could remain just dreams forever. With both our science investment strategy and our education system, we hold the key for going one way or the other.

Science needs to be understood as an integral part of society, both culturally and economically. Consequently, it should be clear that it is the society at large who 'owns' science. The essential role of a scientist is to increase the knowledge of the society rather than his/her own, which means that not only his/her understanding of scientific matters is relevant, but also their communication to others.

Scientists still have an image problem within our society, and are sometimes perceived as members of a distinct strange species, only losely related to humans, and incapable of human communication and social interaction. This detachment makes careers in science generically unattractive, and can be the source of mistrust. Given that information is the enemy of prejudice, we therefore need to work with the media to portray a proper picture of what scientists are actually doing over their work day, and show that they are ordinary people who can socialize. Being a scientist is not about being an incredibly clever egghead (quite unlike ordinary human beings), but about curiosity paired with honesty. The fact that questions that lack of practical relevance are commonly referred to as "academic" is a reflection of a bad reputation – in particular the disability to engage in a dialogue with the general public – that needs to be overcome.

On research funding, a 'Haldane Principle' in the form of "researchers rather than politicians should take the decision" is frequently quoted, which is commonly believed to have emerged as government policy from the so-called 'Haldane Report'[2] from 1918. The suggestion of such a

[1] e.g. interview with Professor Penny Sackett, Chief Scientist for Australia, by ABC Sydney, http://www.abc.net.au/local/stories/2008/10/03/2381204.htm

[2] Ministry of Reconstruction, Report of the Machinery of Government Committee, Chairman: Richard Burdon Haldane, 1st viscount of Cloan, Cmd 9230, H.M.S.O., 1918

principle in this report is however just a myth, born in the 1960s.[3] John Denham, MP, considered the three key elements of the Haldane Principle for the world of the 21st century to be: ''First, that researchers are best placed to determine detailed priorities; second, that the governments role is to set the over-arching strategy; and third, that research councils are 'guardians of the independence of science'''[4]. David Edgerton becomes delightfully explicit on this concept by stating: ''Whether these principles actually are those of 'Haldane' is a nonquestion; whether they are good principles is certainly a question. In my view the first would be acceptable to Madame Ceaucescu; the second is highly debatable in relation to university research; the third, if the genuine view of government, would imply there are no independent universities or learned societies or academies- government will decide who the guardians are, and appoint them! Again, 'Haldane' is for some a great truth from 1918, for others an antiquated albatross around the neck of British research policy. It is of course neither of these things.''[5] I can confirm that he is not alone with his view.

Professor Lord John Krebs stated that it is ''for scientists to judge what are the most innovative, creative projects that are being offered at the moment and to fund those''.[6] It seems to me that Professor Lord Krebs assumes that all scientists would act in the same way he does, and judge proposals solely on scientific criteria such as innovation and creativity. It is however observed that in a competitive arena, many researchers have vital interests in the decisions about research funding themselves. It is almost impossible for a specialist in a research field to assess a related proposal without the result having an impact on himself. It cannot surprise that scientists are arguing in favour of their own interest, which in my opinion corrupts the whole currently-applied peer-review system. While specialists are required to check the technical feasibility, those are the least suited to judge on the priority of their own area of expertise against others. The scientific and societal merit of research work can only objectively be assessed by a panel whose members are free from particular interests. Moreover, increasing distance from a special area provides a better opportunity to see the wider context.

These thoughts get us back to the issue of 'ownership' of science and the role of the society. If research has an immediate economic impact in the form of products or services, consumer choices on the market demand innovation. Besides short-term or long-term economic benefit, our society however calls for more: there is also 'consumer' demand on answering fundamental questions (whatever the rationale behind this may be). In fact, the society regards research in fundamental science to be beneficial. Otherwise, no government would provide financial support. However, current models on science funding almost neglect the role of the 'consumer', i.e. the society at large, who asks for knowledge besides any foreseeable economic benefit. Would not be it right to give the (interested) wider public a say on general directions of science funding that are better decided from an independent viewpoint rather than with specialist knowledge? We also have to ask ourselves whether we are serious about the principles of democracy if only scientists are entitled to decide about science issues. Should defence issues only be decided by army officers? Should we abandon parliament at all in favour of expert panels?

As Professor Lord Krebs said, we need to identify those projects that are the most innovative and creative.

Unfortunately, current structures pose substantial obstacles to achieving this goal, which is essential for the economic and cultural prosperity of our nation, and will determine where we will stand in international context. With 'established' researchers defending their field, innovation will eventually come to a standstill, and new upcoming ideas cannot be realized. We should remember that Charles Darwin pointed out that survival of a species is linked to the ability to adapt to changing environments.[7] It is therefore mandatory that we give science the largest

---

[3] e.g. David Edgerton, History & Policy, http://www.historyandpolicy.org, ''The 'Haldane Principle' and other invented traditions in science policy'', July 2009; based on theWilkins-Bernal-Medawar Prize Lecture, given in April 2009 at the Royal Society

[4] John Denham,MP, Secretary of State for Innovation, Universities and Skills, Speech on ''Science Funding'', Royal Academy of Engineering, 29 April 2008

[5] David Edgerton – (as above)

[6] House of Commons – Innovation, Universities, Science and Skills Committee, ''Putting Science and Engineering at the Heart of Government Policy'', Eight Report of Session 2008-09, Volume II, 23 July 2009 (HC 168-II), Oral Evidence presented on 25 Feb 2008 by: Professor David Fisk, Imperial College London, Professor Lord John Krebs, a Member of the House of Lords, University of Oxford, Professor Julia King, Aston University, Professor Lord Martin Rees, a Member of the House of Lords, President of the Royal Society

[7] Charles R. Darwin, ''On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life''. John Murray, London, 1859

possible freedom and opportunities to evolve. If one accepts the fundamental principle of innovation being the driver of the economy, the aim of maintaining prosperity calls for providing conditions that render a maximum of innovation the winner of any evolutionary process.
Under the current circumstances, a reasonable and well-meant career advice for students is to follow the money, but should we not change the rules in order to make the money follow their ideas instead? Rather than behind-closed-door discussions in committees, we need amaximum of transparency on decisions about science funding, and it is also worth noting that intelligent life does not start at professorial level. With a PhD, one is a qualified researcher, and with age 18, one is a qualified citizen.
I was delighted to see that the UK Deans of Science recently formulated a similar view on open and transparent consultation, and how to move forward from that: ''The views of the science and engineering community must be taken into account when science policy is formulated. We offer no magic bullet to show how this can best be achieved. There has often been a tendency to rely on the same ''great and good'' individuals and organisations that, perhaps, can be relatively conservative in outlook and lacking in more forward thinking. Such reliance on the great and good also tends to ensure that the views of the most radical thinkers, younger scientists and some minority groups are not heard. It is important that a full range of individuals and organisations are offered the opportunity for engagement in the development of policy.
Whilst Governement calls for comment can be helpful, we believe that rolling programmes of meetings with a wide range of individual scientists and engineers, with relatively open agendas, and where the participants can be confident that the consultation is genuine and that decisions have not already been made, could offer a way forward. Such an approach would certainly be preferable to commissioning one individual or organisation to produce, by consultation with a handful of others, a document that effectively becomes policy on its publication date. Of course, following the fuller consultative process that we suggest would mean that the Government (not the permanent civil service staff) would have to weigh up the outcomes and make final decisions on the way it wished to move forward.''[8]
There are some fears about changing an 'established' and traditional system (no matter how bad it is), and doubts on whether there is a well-informed public able to take appropriate decisions on science issues.
On the other hand, nobody has ever proven this to be an utopy. In any case, we will not lose anything by carrying out pilot studies.
If one reads the Haldane Report, one actually finds important recommendations that appear to be mostly ignored for almost 100 years. The statements on 'Research and Information' culminate on the call for a ''separate Department of Intelligence and Research'' which ''would take its place among the most important Departments of Government''.[9] In fact, 'Research and Information' is seen as one of the 10 main divisions of the business of Government, alongside 'Finance', 'National Defence', 'External Affairs', 'Production, Transport, and Commerce', 'Employment', 'Supplies', 'Education', 'Health', and 'Justice'.[10] The Haldane Report stresses the ''full responsibility of Ministers to Parliament''[11], but advocates the establishment of 'Advisory Committees': ''But the preservation of the full responsibility of Ministers for executive action will not, in our opinion, ensure that the course of administration which they adopt will secure and retain public confidence, unless it is recognized as an obligation upon Departments to avail themselves of the advice and assistance of advisory bodies so constituted as to make available the knowledge and experience of all sections of the community affected by the activities of the Department.''[12] This is a quite remarkable statement, not only because of its focus on public confidence, but moreover because it does not call explicitly for expert committees. Therefore, in a modern context, where the general public is seen as affected by governmental activities, it can be interpreted as the concept of public dialogue in its infancy stages. We also need to be aware of the fact that the political responsibility cannot lie with scientists, which would mean that they

[8] House of Commons – Innovation, Universities, Science and Skills Committee, ''Putting Science and Engineering at the Heart of Government Policy'', Eight Report of Session 2008-09, Volume II, 23 July 2009 (HC 168-II), Memorandum 16, Submission from UK Deans of Science, paragraph 7
[9] (see Ministry of Reconstruction, Report of the Machinery of Government Committee, Chairman: Richard Burdon Haldane, 1st viscount of Cloan, Cmd 9230, H.M.S.O., 1918) - Part II, Chapter IV, paragraph 74
[10] (see Ministry of Reconstruction, Report of the Machinery of Government Committee, Chairman: Richard Burdon Haldane, 1st viscount of Cloan, Cmd 9230, H.M.S.O., 1918) - Part I, paragraph 55
[11] (see Ministry of Reconstruction, Report of the Machinery of Government Committee, Chairman: Richard Burdon Haldane, 1st viscount of Cloan, Cmd 9230, H.M.S.O., 1918) - e.g. Part I, paragraph 37
[12] (see Ministry of Reconstruction, Report of the Machinery of Government Committee, Chairman: Richard Burdon Haldane, 1st viscount of Cloan, Cmd 9230, H.M.S.O., 1918) - Part I, paragraph 34

effectively convert to being politicians. Instead, links between politicians, the civil service, and the science community should be fostered, in order to work together for the benefit of the nation. In 1972, Lord Rothschild pointed out that: "However distinguished, intelligent and practical scientists may be, they cannot decide what the needs of the nation are, and their priorities, as those responsible for ensuring those needs are met."[13] This observation led to the suggestion of a customer-contractor principle for scientific research where the Government Department or Government Chief Scientist takes the role of the 'customer' who commissioned 'contractors', namely the Research Councils and Universities, to do research.[14] While I tend to agree with the premise, I arrive at a different conclusion. Rather than the demand arising from government authorities, it is the public at large that should be seen in the function of consumers in a research market model, who make choices amongst the curiosity-led options for innovation brought forward by scientists.

There are good reasons for asking about "impact" of scientific research. However, there is neither a common definition of "impact", nor do we appear to understand how to measure it. While several Research Councils are now asking applicants to include a statement about potential impact of their work, they provide almost no guidance, and leave it to the applicant to interpret the scope and meaning.

In any case, no variant of bibliometrics can ever properly reflect the true impact of scientific work, neither an economic one, nor a cultural one. So far, I have not seen a single statistic derived from citation counts that is free from leading to absurd results, and the long unsuccessful search for such 'magic number' raises the suspicion that it may not exist at all. Citations counts no better reflect the quality of scientific work than viewing figures reflect the quality of TV programmes. Moreover, most relevant for society is the lasting impact, which is not at all related to the attention that scientific publications receive from specialists during the first 5–10 years after the publication date. One might also question whether the specialists' vote is that meaningful or whether "impact" rather arises when research work is recognized by someone who has never worked in the same area. Making decisions about academic careers on criteria delivered by the bibliometrics "industry" could be called a useless exercise of an academic self-appraisal scheme (where 'academic' has the same negative undertone as in 'academic question'), if it were not prone to foster bad practice in science. I am tempted to ask whether a purely random process, such as throwing a dice, would actually provide a better result. Bibliometrics reflect on both personal working style and the specific dynamics of a field, and thereby are a characteristic of a research profile. However, there are many roads to success and one specific profile cannot be considered better than the other. To the contrary, the success of a team frequently gains by involving people with different and complementary profiles. If we are interested in a science base subscribing to the principles of honesty and collegiality, the use of bibliometrics for judging on scientific work and academic careers needs to be abolished sooner rather than later. We need to think very carefully about whether we would like to grow a generation of scientists who aim at maximizing (more or less silly) performance indicators, or lend our support to those who subscribe to the fundamental principles of good scientific practice and aim to transform their curiosity into societal benefit. The Committee on Freedom and Responsibility in the conduct of Science (CFRS) of the International Council for Science (ICSU) has recently warned against the uncritical use of publication metrics in evaluating scientific performance, and raised concerns that "current policies and practices may be having serious effects on the quality of scientific work in general", while suggesting that "the debate is widened to the full international scientific community".[15]

Rather than reducing publications to simple numbers, there happens to be no way around reading them.

One can get a sensible picture of a scientist by carefully studying a few (!) core publications with respect to several criteria such as originality, clarity, rigourosity, or relevance (and probably others as well). We should however not forget that scientific publications are not the only output of research work. A more complete picture would be gained by also reviewing presentations given

[13] Cabinet Office, "A framework for Government Research and Development", November 1971, paragraph 8

[14] House of Commons – Innovation, Universities, Science and Skills Committee, "Putting Science and Engineering at the Heart of Government Policy", Eight Report of Session 2008-09, Volume I, 23 July 2009 (HC 168-I), paragraph 142

[15] ICSU committee on Freedom and Responsibility in the Conduct of Science (CFRS), Statement on publication practices and indices and the role of peer review in research assessment, July 2008

to various specialist and nonspecialist audiences as well as involvement with the wider public, the media, or any part of our society.
This would also take care of the fact that research work does not end with obtaining results, but necessarily involves their communication. In accordance to what I stated earlier, I would consider a mixed assessment by both a specialist and a non-specialist panel to yield the most appropriate result. Such would require a non-negligible amount of work, but good results usually do not come without a price. However, I think that this is what needs to be paid in order to keep, create, and maintain a science base that will be suited to face the future challenges. A simple and straightforward assessment procedure by means of a well-designed electronic system might render such an approach feasible.
A predictable "impact" is at odds with the nature of fundamental research, where a characteristic feature is just the unpredictability. It seems to me that "relevance" or "relation" to the goals of the society are more suitable a-priori characteristics for proposed lines of research. I would think that, even without a clear definition of assessment criteria, a well-informed society is able to set priorities along what it considers most relevant, which not only covers applied but also fundamental research, by a rather intuitive approach.
Humanity has survived on such strategies since its existence. Everyone who disagrees is welcome to prove me wrong.
An over-long 'qualification phase' severely limits the attractivity of academic careers. The lack of any job certainty before the age of about 40, paired with the expectation to relocate on a rather regular basis, is not a good basis for a family life. For women, this is an even more serious issue than for men. Moving on from one job to the next can only be a model in a flourishing economy where lots of good jobs are waiting for candidates, and this is obviously far from reality. If we aim at fostering independent thinking (and science should not be built around people who require detailed instructions), self-directed research should be mandatory immediately after a PhD, if not earlier. The standard track of identification of the future generation of leading scientists should take place within the first 5 years after a PhD, and these then deserve career support and should be given financial security. However, this must not mean that a scientific career is made impossible to anyone who pursues alternative paths after the PhD. To the contrary, other forms of experience can be quite valuable, and any thriving university department lives from a diverse mix of different personalities.
We currently see too much weight on discussions about research facilities and research areas, while the vitality of a research landscape in first instance relies on people. We should moreover move from a project focus to a people focus. Good scientific work needs a substantial build-up, and any reasonable researcher will aim at achievement rather than failure. Why do we waste most valuable human resources by forcing researchers to think within short-term projects, define short-term goals, and even worse, demand that specified results are delivered? Are those not grown up enough for knowing how to do their job? It is not a secret that less predictability and higher risk comes with a larger potential gain. If we fear risks, we will never achieve excellence. This also means that we have to accept failure. One is not a bad scientist because a promising approach turns out not to be successful; one would however be a bad scientist, had one not tried. As a consequence, one might want to shift money towards people-focused schemes like the fellowships and professorships offered by the Royal Society, or give money directly to universities for supporting research excellence.
We also appear to live in an inflationary period of long-term science roadmaps. While the larger science facilities need some advance planning, longer-term strategic considerations are frequently not meaningful for smaller ones. It is far more important to be able to react to new developments on as short as possible time-scales, and a short-term strategy reserve fund should be set aside for this. The predictive power of roadmapping exercises on time-scales exceeding 10 years is not that great, and it can be empirically tested by looking at those of the past. While the imagination of what could happen in 20, 50, or even 100 years time gives indispensable insight for today's decisions, it should be the aim to realize scientific projects on shorter time-scales, if at all possible. Moreover, one needs to be clear about where predictable steps end and speculation takes over.
It is not clear to me why science should be split amongst the large number of Research Councils, which creates additional obstacles for research that cannot be uniquely allocated to one of them. The remits of the Research Councils have been repeatedly under debate, so let me just add some thoughts. After an era of (over-)specialisation, we are about to re-discover that science is essentially a continuum, and the division into disciplines is as arbitrary as dividing the spectrum of visible light into colours (where there is a large variety of cultural choices). I would therefore find

it more natural to have a single 'Research Grants Council', while a separate organisation is responsible for the operation of National Science Facilities.
However, a proper discussion of all advantages and disadvantages of any specific organisational structure would be a rather lengthy process itself. I feel that we should have it, nevertheless. . .
A final thought goes to research with foreseeable commercial exploitation. If research has clearly defined economic impact, it can already been driven by the market forces, financed at the end by the consumer through commercialisation. Provided that there is no fundamental conflict between academic and commercial interests, private capital could carry such research work.
Public funding is far more important for research lines that do not show foreseeable economic benefit, or for which the benefit is too far away in time for being attractive to private investors.
Government interference with market forces can even be counterproductive.
Commercial companies can lobby for governmental support of technologies that are of little benefit to the society and which are not supported by the consumer. If this is successful, taxpayers' money will move into private pockets with the only public benefit of an expensive and inefficient employment programme.

Summary of recommendations:
o keep children curious, and encourage themin developing their personality and gaining self-confidence,
o shape a proper image of scientists in the society with help of the media,
o assess the technical feasibility of a research proposal by expert review, but leave the judgement on the scientific and societal merit to a panel of scientists outside the field and lay(wo)men,
o realize two forgotten(?) suggestions from the Haldane report, adapted to the 21st century:
- establish a Department of Research (Part II, Chapter IV, paragraph 74),
- retain public confidence by having transparent processes in Research Councils with both expert advice and involvement of the general public as representatives of our society (a modern version of Part I, paragraph 34),
o do not devolve the political responsibility to scientists, who then would factually convert to politicians, but foster communication and links between science and politics to work together for the benefit of the nation,
o adopt a market model for funding of fundamental research by listening to the general public as 'consumer' of knowledge,
o abolish bibliometrics as a means for assessing scientific research,
o make self-directed research mandatory in academic-related positions immediately after a PhD, if not earlier,
o replace the over-long 'qualification phase' with an earlier selection process, but allow off-the-track entry,
o identify young talent at latest 5 years after a PhD and provide a clear perspective,
o put investment into people before investment into facilities,
o consider shifting money from research grants to universities for direct support of research excellence,
o create a short-term strategy reserve fund in order to allow prompt reaction to emerging developments,
o consider a single 'Research Grant Council' alongside a 'National Science Facilities Council',
o consider private funding as a major source of income for research with foreseeable shorter-term economic benefit, and provide substantial public support for a strong research base in the fundamental sciences for which there is no opportunity of raising venture capital.

Acknowledgments
I would like to acknowledge several discussions with early-career researchers over the last three years.
Moreover, I would like to thank the organisers and lecturers of the extremely insightful professional development courses on "Innovation and the Business of Science" offered by the Royal Society in cooperation with Imperial College London, in particular Nelson Philips and Brendan Barker, as well as on "Science and Society" by the Royal Society in cooperation with the Open University, most notably Rick Holliman, Jeff Thomas, Matthew Harvey, and Chloe Sheppard, from both of which I drew a lot of inspiration.

New and Renewable Energy Centre (NaREC)

NaREC response to the IET request for help in responding to the Royal Society consultation
"The Fruits of Curiosity: science, innovation and future sources of wealth".

The long-term direction of policy for science

2. Which elements of policy for science and innovation over the past 10 years have been successful and should be maintained? Where is there room for improvement?

Total R&D spend on science and engineering in the UK has been on an upward trend since the early 1990s and was around £5.9bn in 2005/6 of which about 71% was government funding, 15% from charities, 8% from overseas and only 5% from industry.

The UK total expenditure on R&D (Gross Domestic Expenditure, GERD) was 1.76% of GDP in 2004 compared with 2.41% across the G7 as a whole; only Italy out of the G7 spends proportionately less at around 1.1%.

(Source: SET data, Department for Innovation Universities and Skills)

Energy research, in particular, has been a casualty of privatisation; when CEGB (electricity) was privatised, the generic research on electricity generation was cancelled and has not been picked up by private industry. Government sponsored research has not filled the gap. We are now in a very difficult period where we need new technology to fill a growing energy gap, but the development of these technologies is lagging far behind our immediate requirement for new clean energy provision and of course we rely greatly on imported technology.

Market based support mechanisms, such as tradable certificate schemes, seem to be slow at encouraging investment. Rather, they improve the short term operating behaviour of the industry but do not appear to be particularly effective at bringing forward new investment. The EU ETS, the various supporting mechanisms aimed at controlling emissions and the UK Renewables Obligation are particular examples of measures that involve immediate effect on customer prices but do have not led to commensurate new capacity. It is of course possible to speed up deployment of emerging technology, where risks are relatively low, by introducing multiple ROC's. This may accelerate deployment, but is based on trial and error and may require more than one attempt to achieve the right level. This is clearly time consuming. Direct support mechanisms such as feed-in tariffs have been more successful in terms of speedier development of new technology markets as they considerably reduce the effective cost of capital. These mechanisms do not support directly early stage innovation but can support the commercialisation of new technology.

Mechanisms aimed at introducing new technology on a national or international scale generate significant costs that have to be absorbed, eventually by the public at large. There has to be a balance struck between the cost efficiency of the mechanisms and the timescale over which change is required; in the case of both climate change mitigation and energy infrastructure, the speed of implementation is becoming critical, which require a change in the support mechanisms to speed up delivery, but at further increase in cost.

While Government support for R&D has increased, so has the number of organisations responsible for the support programmes, each with its own gate mechanisms and drivers. In energy there are number of Government departments responsible for programmes aimed at Climate Change, Energy Use, Renewable Energy and Energy Technology, there is a real need to address the inefficiencies and confusion that results.

Science, innovation and wealth creation

12. How can we strengthen science and innovation in all parts of the private sector in the UK, and further improve the exchange of knowledge and expertise between the public and private sectors?

Essentially the linkage between academia and industry needs to be improved; the private sector is reluctant to invest in risky R&D and therefore needs to connect with the academic sector more effectively. The reverse is also true; the academic sector needs to work more effectively with the private sector if its academic research is to be taken more seriously. In an ideal situation the differing ethos of the two sectors, the idea of knowledge development and transfer and publication in the public sector and the demands of private sector for commercially focussed research and the issues around IPR/confidentiality, would present opportunities to both sectors; however this is not always the case and can hinder relationships. Moreover, a particular barrier to the development and commercialisation of research projects is the different skills required at each stage. Only rarely does a research scientist have the expertise to grow a company from a start-up, employing three or four individuals, into a large enterprise, capable of having a large impact on the economy. Indeed, this problem is often exacerbated by the academics not wanting to "loose control" by accepting the injection of capital necessary for rapid expansion. Similarly, private investors often do not understand the working practices of academics, with their pursuit of "interesting" problems and/or perfection, rather than the production of "good enough" technology.

Publicly sponsored secondments between industry and academia in key policy areas could help both industry connect with academia and researchers to understand the needs of the private sector, particularly for research that could lead to commercial exploitation. Currently there is no satisfactory career development for research fellows who might live on two or three fellowships consecutively and then have to abandon a research career; secondments between academia and industry might help avoid this potential dead end and help stimulate new research areas.

Publicly sponsored bursary schemes to encourage Master's/PhD/Post doctoral research could help researchers earn a sensible income, coupling this with a student loan write off scheme would make it easier for high quality students to take up Masters/PhD level research. Research students in science and, particularly, engineering, in British universities, are mostly from overseas and funded by their governments. This is because newly graduated UK students with debts of £20k are reluctant to take on an additional £30k of debt to see them through their research course. In Denmark, for example, research students receive a stipend.

Expensive publicly funded programmes, such as the bureaucratic Foresight programme which produced little practical output, can also reinforce the private sector's reluctance towards investing in research. Unfortunately, energy research by EPSRC has not been co-ordinated well despite around £394m being spent since 2003 (Source: EPSRC, support by socio economic theme http://gow.epsrc.ac.uk/ListThemes.aspx). Curiosity based (blue sky) research has not been funded, rather proposals from established, safe pair of hands, group leaders has been favoured.

We would suggest to counter this, ten per cent of funding could be set aside to support purely blue sky research; unfortunately the private sector is reluctant to support this kind of research, for example the BP blue sky fund was cancelled some years ago as it did not contribute to the "bottom line". Academic researchers need to be given freedom and finance to try out new ideas outside the mainstream constraints of a subject. Most new ideas come at the edges of subjects, nano technology, DNA etc. The research councils need to be brave and fund more risky research because the private sector will not; this could also encourage the private sector to take more of an interest in academic research.

Often universities insist that all intellectual property resulting from research, or collaborative research with industry, is their property. Even visiting lecturers are made to sign away their rights. This stifles cooperation with companies or individuals. Where research contracts are placed with universities, confidentiality clauses prevent research students presenting or discussing their work at conferences. This destroys the free flow of ideas which is the opposite of what a university should stand for. In any case conferences are so expensive that very few academics attend them. IPR should really only become an issue when there is a realistic chance of commercial exploitation.

It is important to recognise that without researchers we would not have innovative new ideas coming forward and the best way to encourage people who come up with the ideas is to reward them appropriately, rather than trying to claim rights over their thinking before they have come up with the ideas in the first place and then to severely limit the possibility financial reward. With the long term future in mind young researchers should be encouraged, if necessary at the expense of the established figures, and good ideas rewarded financially and with promotion.

Working to publicise science and the excitement of new discovery is vital if research, and the developments that come from it, are to be encouraged. This is best done via the media and particularly television, yet young university teachers are ill advised to go down this route as they can finish up not being taken seriously by their colleagues. The universities should encourage and help researchers publicise their findings by working with the media more effectively, perhaps by getting more involved in the commissioning and production of television/radio and internet based programmes in an advisory capacity and strengthening their links with published media, particularly the more populist publications.

In addition to the UK Government support, there is considerable further R&D funding available from EU programmes. Government should ensure that the UK gets the maximum benefit from these programmes by dedicating resource to the targeting of this funding. This should be in the form of having individuals whose responsibility and success is measured by their performance in attracting this funding to UK businesses.

13. How can we improve the scale and contribution of private sector R&D?

For the private sector to invest more in research, particularly where returns may take a long time to materialise (indeed there may not be returns in some cases and investment may have to be written off) the risk taken on in investing in technically challenging or long term R&D needs to be recognised. Major tax breaks would help (100% relief) to encourage investment in research in key policy areas for example, cleaner/renewable energy and energy efficiency, environment, particularly adaption to climate change. This could be coupled with at least 50% and up to 100% capital grant funding for specific key projects at a commercial demonstration stage that have the potential for large scale industrial application/market/job development for example, CCS, tidal turbines, 2nd generation biofuels; perhaps in return for a share in the business. Essentially the development of ideas towards commercial realisation costs a lot, usually at a time where income is limited or even non existent, especially in start-up businesses. For particularly challenging ideas if private investment is to be encouraged someone has to underwrite the risk.

There is scope for price controlled industries to be encouraged to undertake more research as the simple RPI-X approach does not encourage innovation, as the benefits are surrendered at subsequent price reviews. The OFGEM innovation incentive could be expanded and extended.

To give an idea of the scale of support that could be needed, to build a fully commercial scale demonstration CCS plant dealing with the full output from a 1500MW coal fired power station could cost around £1bn or around a sixth of the UK's total spend on science and engineering R&D. More investment from industry will only come if there are the support signals from government for particular policy areas and confidence in a market for new technology. In terms of cleaner energy/electricity provision, which is a critical area if we are to secure the UK's energy supply base whilst reducing emissions, the extra support for wind through working with EIB and £10M research funding announced in July is welcome; however there needs to be support across all the key 'clean' energy sectors, particularly cleaner coal/CCS, tidal and new nuclear if further investment is to be encouraged. Nevertheless, there should be incentives on these demonstration projects to produce results, rather than just cover the cost of building generators. As such, forms of support, such as long term banded feed-in tariffs could be a sensible way forward for technologies at early stages of development. Government announcements on the availability of their funding can be confusing as they do not invariably relate to "new" money.

14. What initiatives (e.g. tax credits) have been successful or not with regards to supporting innovative businesses in the UK? How can the UK better support business?

Tax breaks are helpful and should be efficient as they provide release of untaxed funds provided they are invested in line with criteria set; the criteria should be aimed at specific policy outcomes and be rigorously interpreted if they are to be effective, assuming the policy aims are sensible which is not always the case. Tax breaks are essentially less likely to be effective at encouraging investment into higher risk areas for research where the short term returns are not easily identified.

Capital grants, at a high proportion of the overall investment required, can be very helpful for higher risk R&D; however, a common requirement for match funding and collaboration can be an issue where there is a strong potential for commercialisation, but see above for the need to regard successful operation, rather than just construction.

The wider consequences of encouraging the rapid up take of new technologies through powerful fiscal stimulus should always be thought through before the policy is implemented; for example, the unintended consequences of supporting the biofuels industry in this way have lead to concerns over competition with the food sector and issues over the carbon balance of such fuels.

Continuity of funding is a key issue particularly with developing an idea from the academic interest stage to pilot stage and then on to commercial demonstration at which point commercial funding can be sought. Current funding arrangements are very 'stop/start' where once initial seed funding for pilot scale development has been exhausted development tends to stop, perhaps for a year or so whilst further commercial demonstration funding is sought, projects then often reach another stop point until full commercial funding can be obtained. However, a good example of initial support is the 'proof of concept' funding available from One NorthEast which can provide up to £100,000 to bring an idea to the stage where it can be shown to work effectively; a vital support mechanism for new projects in the North East.

Identifying and accessing the most appropriate 'gateway' to funding can be very difficult for early stage project developers; the Technology Strategy Board could play a stronger role in this.

It is striking that the only UK based energy research centre supported through the 'Large Research' route is Culham Laboratory which looks at nuclear fusion. If new, renewable and cleaner energy are to play their vital part in helping to reduce our carbon dioxide emissions surely the sector would merit a 'large' research centre or project which could act as a focus and stimulus for new, innovative energy technology developments? Because of market failures and to encourage innovation, the UK must invest in the provision of adequate and appropriate test facilities to accelerate technology development.

The disparate nature of responsibility for 'energy' spread across many government departments and funded organisations, for example DECC, DEFRA, DBIS, the Carbon Trust, the Energy Saving Trust, the Energy Technology Institute, UKERC, the research councils etc, causes confusion in terms of policy development/ delivery and in sourcing appropriate funding.

I would also add something about the need for more ,opportunities for investors and ''inventors'' to meet. In particular, developing a cadre of individuals particularly skilled at leading companies at different stages of development.

Government should encourage through the Regional Development Agencies and other organisations, the opportunity for investors and investors to meet. This should ensure there is a two way flow of information and the development of people skilled at leading companies throughout the various stages of development.

NaREC
September 2009

National Science Learning Centre

Royal Society 'Fruits of Curiosity'
The major action areas for improving science and mathematics education

The premise is that a high quality science base depends on both the supply of future specialists and a scientifically aware and numerate population that understands and supports scientific and technological innovation.
This means the system must be configured to deliver science and mathematics to all, some of whom will become the new generation of scientists.

Action Area 1: Teachers
Why this matters
'No education system can be better than the quality of its teachers' [Barber for McKinsey]. The best science teachers – especially for stimulating bright students – are subject specialists with great teaching skills.
This means recruiting subject specialists and giving them high quality training in both subject knowledge and teaching skills.
Teachers have become over compliant and expect to be told what to do. They need to be given less top-down orders and more autonomy so they can take back their professionalism.
Progress has been made in improving recruitment of specialist teachers and converting non specialists, and in the provision of high quality CPD for science teachers, particularly through the Science Learning Centres.
Further action is needed to continue recruitment of specialist teachers, using the opportunities presented by the recession, and to maintain the momentum towards improved participation in subject based professional development by teachers. Where there is a shortage of subject specialists, extended professional development is needed to equip teachers with knowledge to teach outside their specialism.
An important area for further action concerns the autonomy of teachers. Leadership is needed at both national and school level to ensure that the opportunities presented by the less top-down approach following the abolition of the National Strategies, and the potential freedom following the abolition of key stage 2 and key stage 3 tests, are taken in practice.
It will be very important to improve the leadership capacity at school and college level in a context where there is less national intervention and more local autonomy. This will be a priority for the Science Learning Centres.

Action Area 2: The Curriculum
Why this matters
The science curriculum framework in England is broadly right in the provision of a suitable science education for both those who will continue science and those who will stop studying at 16.
Where the curriculum is defective is because of the way it is delivered in practice, with the back-wash effect of high-stakes assessment being a contributing factor.
Students may not be offered the most appropriate options to keep their post 16 opportunities open, and even when they are they offered they may not be taught as intended.
Aside from teacher quality, the commonest cause of poor delivery is assessment that is unfit for purpose.
Progress has been made in producing a secondary science curriculum that potentially meets the needs of generalists and specialists.
Further action is needed to

- Strengthen the subject based expertise of the system that sets the curriculum (currently carried out by QCDA), and to ensure a coherent framework from primary to post 16.
- Ensure that all secondary schools offer Triple Science (currently only around half of them do)
- Ensure that all primary schools offer a full science entitlement
- Reach a consensus on the nature of the second mathematics GCSE and implement it as quickly as possible

Action Area 3: Assessment
Why this matters

The assessment and accountability framework is the water that teachers swim in.
We have to accept that teachers will always want to maximise their students' performance in external tests. So those tests must be fit for purpose, not just driven by what is easy to measure. Some testing is of poor quality, especially: 'How Science Works'; mathematical aspects of science; and practical work.
The assessment framework in science gives students few opportunities to follow their own interests, or show what they can do to authentic contexts. Assessment has been too often designed to measure that which is easy (eg, recall) rather than that which is valued (eg, synthesis of complex skills).
Progress has been made in addressing inadequacies in science GCSEs in order to restore confidence in them.
Further action is needed to

- Address the problem of the serious shortage of skilled question setters, particularly in questions on 'How Science Works'.
- Address the problems caused by the incentive for Examination Boards to compete by making their exams easier
- Put in place frameworks to replace the key stage 3 tests in science and mathematics and the key stage 2 tests in science with arrangements which incentivise teachers to exercise autonomy and reduce the amount of 'teaching to the test'
- Improve and increase the mathematical content of science GCSEs and A Level examinations.

Action Area 4: Ethos of schools and colleges
Why this matters
Successful schools and colleges create an ethos that celebrates hard work and academic success by girls and boys of all backgrounds.
Science and mathematics are seen as challenging subjects, but with high status. This challenge and status needs to be celebrated, not run away from.
Progress has been made in:

- Improving the ethos towards science and mathematics in some schools and colleges, for example science and mathematics specialist schools
- Significantly increasing the proportion of secondary schools that offer Triple Science and the number of pupils taking it.

Further action is needed:

- To make faster progress towards the situation where every school offers all three GCSE science options (core; core plus additional; triple science)
- To remove perverse incentives which discourage schools and colleges from advising young people to study science and mathematics because they are perceived to be harder
- Incentivise schools and colleges to create an ethos which celebrates the intellectual challenge of science and mathematics rather than running away from it.
- Encourage primary schools to use the Primary Science Quality Mark to keep the profile of science high.

Action area 5: Market pull
Why this matters
STEM qualifications open the door to the widest range of fulfilling and well paid careers – but students, parents and even teachers do not always realise this.
Universities and employers need to be much more explicit about which subjects they prefer.
Careers awareness needs to pervade teaching.
Schools and colleges need to show students how science is used by real people in the real world.
Progress has been made in:

- Showing students how science is used in the real world, through a more relevant science and mathematics curriculum and more authentic cross curricular links in primary schools
- Through STEM ambassadors providing role models for young people to show them the opportunities available for people who study science and mathematics

Further action is needed:

- By universities and employers to be more explicit about the subjects which they prefer students to have studied at A level

- To provide high quality careers advice through all available channels (including subject teachers) to make students aware of the range of careers available to those who study STEM subjects.
- To support teachers in the use of relevant, cutting edge science through collaboration with scientists

Action area 6: Primary science
Why this matters
Attitudes towards science and formed very early – often before the age of 11. High quality primary science teaching can sow the seeds for a lifetime's interest in science.
Conversely, poor teaching or excessive teaching to the test can turn pupils off before they have even been turned on to science.
As a core subject, science has been high on primary schools' agendas, but increasing focus on Mathematics and English has tended to downgrade its importance.
Progress has been made: in creating a primary science curriculum that is coherent with the secondary school curriculum and embeds an enthusiasm and understanding of science. Good practice has been established in many schools, with effective leadership coming from the Science Learning Centres and the Association for Science Education. Attainment by 10 year olds in England is high by international standards.
Further action is needed: to secure a curriculum that is coherent with the evolving secondary curriculum and emphasises scientific investigation. The perceived gap left by the removal of key stage 2 tests needs to be followed up so teachers take advantage of greater freedom. Teacher assessment skills will be vital. Headteachers need convincing of the importance of primary science now there are no longer any tests. The Primary Science Quality Mark should be promoted.

John Holman
National Science Learning Centre 9 September 2009

Pfizer

The Fruits of Curiosity: science, innovation and future sources of wealth
Call for Evidence

We at Pfizer are very pleased to be part of the Royal Society's Fruits of Curiosity "study into the role that science will play in equipping Britain to meet the economic, social and environmental challenges of the next twenty years" (*Fruits of Curiosity Call for Evidence).* Britain remains a globally attractive place for companies like Pfizer to invest and to form partnerships in science and innovation. However, this should not excuse complacency in taking the long view in supporting and advancing British science, particularly as concerns are mounting about the underlying health of the scientific community. In order to take the long view, the *Fruits of Curiosity* project should challenge first the framing by which science policy is designed, that is, the investment view of science. This framing hides an implicit characterisation of science as independent activities or events, from which an investment return can be derived. We would argue that this approach fails to capture the importance of interdependencies and the dynamics of exchange in scientific progress, and that, in fact, science is better characterised as an ecosystem than a cumulative series of independent actions.

Moreover, to build on this view of science as an ecosystem, we would suggest that changes in two key domains would position British science well in the evolving international landscape:

- Galvanising sets of concerted actions across disciplines and sectors to meet the "grand challenges" in programmes of limited duration; and
- Increasing the exchange of experts between academia and industry through concrete actions to change individual career paths (and not only students). These policy proposals focus on improving the dynamics of exchange and building a shared agenda. These policies go directly to addressing the health of the science ecosystem, which is core to its long term success. We describe the ecosystem approach and these detailed proposals in the sections below.

Science, innovation and future sources of wealth

For 350 years, the Royal Society has had guardianship of the excellent body scientific that has made the UK a global leader in science and technology. Undoubtedly, these centuries were routinely marked with the challenges and conflict that define the evolution of human social systems. Today we face challenges to British science that concern us all, because they are not challenges of "who" or "what" to lead scientific advance, but "why". Vannevar Bush, in essays such as "As We May Think"[1], established a practice for evaluating the benefits of science to human society in such a way as to underpin the political commitment to continue and expand funding in science. This investment approach to science was instrumental in the growth of scientific exploration in the second half of the 20h century. However, the sting in the tail of the investment approach has been to displace the rationale for science on its own merits in the public understanding, something which has happened to a much lesser extent in the case of the Arts, in contrast. Moreover, there are critics who would argue that the investment approach to science has failed to preserve and advance the body scientific in the UK and elsewhere. Routine articles in the press worry that we have lost our way in science. In a recent letter to the *Financial Times*, Professor Donald Braben led a list of 22 eminent scientists (including seven Nobel Laureates) to make the point explicitly that the investment approach to science has materially harmed the scientific activity and by consequence standing, of British science. "We no longer punch way above our weight."[2] The resulting debate centres on the gatekeeping principles for funding and who should determine them. Less direction in funding are claimed by some[2], more engagement with the users of the translational research is called by others [3]. Both lines of argument fail to examine and reflect upon British science as an ecosystem, and the subtle processes by which it functions.

Science as an ecosystem

As a private-sector public corporation, Pfizer is well-versed in the strategic imperatives of advancing new science and managing a profitable value chain. However, the body scientific of a nation is not the same as an R&D department of a private firm, and the analogies of investment criteria and strategic focus should be applied with great care. Instead, in considering the role for science in Britain (and thus necessarily the health of British science), a more fruitful analogy can

be taken from the more nuanced approach of value chains and open innovation – that is, the innovation ecosystem [4-8].

This approach is quite in keeping with the concept of national innovation systems proposed by Freeman [9, 10] and Lundvall [11, 12], preceded by Abramovitz [13]. The literature on innovation ecosystems explores the relevance of many of the same factors outlined in NIS approaches, but from the perspective of the firm. In both theoretical approaches, the critical dimensions are in the variety of actors, their interdependencies and the viability of structures.

If we seek to understand British science as an ecosystem, we must explore the variety of actors and their interdependencies, as well as the dynamics of exchange between them. Drawing some analogies from nature, there is a need to consider whether the disproportionate strength or failure in one part of the system has knock-on effects to others, and indeed what minimum thresholds of activity are needed to maintain viability. Such an approach would raise important questions to policies that "pick winners" or select specialisations based on their economic potential. Arguably we have not examined British science as an ecosystem, and this may have some important insights into what we can do to advance British science over the next 20 years.

At Pfizer, we have now moved our understanding of our relationships for the discovery, development and production of medicines to that of an R&D or innovation ecosystem (Figure 1). Again, the diagram demonstrates the variety of actors and how they interface at different phases of drug discovery, development, production and marketing. What lies behind this clear structure, however, is the messy process of interdependencies and the dynamics of exchange. Authors like Adner [5] highlight not only the broadened opportunities of engaging fully with different partners, but also the risks and co-ordination costs of moving planning and production of scientific contribution from within the organisation to across organisations and actors. In the UK, Pfizer has developed and managed extensive networks with academics (Figure 2), and whilst this has been an important input to the drug discovery and development process, we do not manage the fate and health of these academic centres. In this sense, Pfizer is one of the many actors within the wider British scientific ecosystem for biomedical research.

Dynamics of exchange

Whilst research has been conducted on variety in innovation ecosystems, there has been relatively less research on the interdependencies and less still on the critical dynamics of exchange. The research that has been done in this regard focuses almost exclusively on the terms for academic-industry linkages, that is, the role of technology transfer offices (TTOs) and intellectual property negotiation. These are critical factors that remain problematic, particularly with the potential for overestimation of value (in the absence of markets) as well as some tensions in governance, where TTOs have competing interests to consider (the academic, the university and, where privatised, shareholders). There has been much research on these issues, and this scholarship must inform the *Fruits of Curiosity* programme of work.

However, we find that there is a further factor – a social and cultural factor – that underscores academic-industry linkages but is rarely recognised. This is the concept of parity, perception and the free flow of people. Arguably, experience demonstrates that ideas travel best in the head of an individual open to new conversations. Putting this in the context of science, the translation of ideas from academic science to industrial science can be best encouraged through the movement of scientists across divides, including between academia and industry. There have been some policy proposals to support this view in encouraging sabbaticals and staff exchanges.
These opportunities and the free flow of scientists will only be facilitated if this is valued by the scientific community, broadly stated. Some have suggested [3] that adjusting the reward mechanisms, such as the new Research Evaluation Framework, to encourage translation of ideas through personnel exchanges will support this, and this is certainly to be welcomed. However, what drives the free flow of individuals between academia and industry in environments such as Silicon Valley and the Boston biotech cluster is not policy intervention, but a genuine expectation that the experience will advance their scientific career in both settings. There is a perception of parity (not necessarily equality, as the work is very different) in science between industry and academia in these globally leading clusters.

We would argue that it is this social and cultural attribution of parity in science between academia and industry that is the underlying rate limiter in academic-industry linkages and the translation of science to commercial outcomes. We have contacted academics and scientific

associations to ask whether anyone has studied the career pathways of scientists to understand if the flow between is predominantly unidirectional (from academia to industry) or whether there is a genuine and fluid exchange. Thus far, we have found no research to test these questions. Moreover, we would welcome a review of the membership of the principal scientific professional communities and associations as such a review may also reveal the extent to which there is perceived parity in scientific discourse.

We believe research of this sort would provide a much-needed "back story" to the evidence called for in question 11, *"Does the standard career-track model need to be re-evaluated? Should we take more account of the movement of skilled individuals between academia, industry and business? ".*

Grand challenges as a means to create a shared agenda

The dominance of the investment approach to science has focused attention on the instrumental goals of science, and as we have noted, there is controversy over the justification and the outcomes of measuring science by what it generates in economic (and to a lesser extent) social terms. Considering science as an investment typically sees impacts to scientific understanding as an upstream input to the roll-out of commercial and practical outcomes. Science leads and industry and society follow to realise the outcomes, applied to new and existing wants and needs.

There is another approach to addressing critical wants and needs, however: the **grand challenges** for science, such as the race to determine longitude, the Manhattan Project, the Moon mission, the Human Genome project and the ongoing work on global infectious diseases. The President of the AAAS argued in 2006, "A public process of eliciting and publicizing Grand Challenges in various fields may be an antidote to this overly conservative trend. We should dare to study hard problems, individually when feasible, and in teams when the challenge demands multidisciplinary effort."[14] Some critics of the introduction of grand challenges argue that this would further accelerate the investment approach to science. However, this criticism seems to be based in the hypothesised continuum of basic to applied to developmental science, where the latter is what is closest to socioconomic need and therefore agendas to answer socioeconomic needs are "bad for basic science". We would argue, as others have, that grand challenges – because they define the problem and not the approach – open the door to unexpected and multidisciplinary approaches that can spur scientific advancement across disciplines. Again, whilst there is much research to measure the economic impacts of scientific investment, more work needs to be done to clarify what scientific impacts there are from grand challenge approaches, as innovation theory identifies that breakthroughs often occur at the intersections of our human understanding.

We would recommend that this analysis accompany the work to address Question 15, *"How do we maintain an appropriate funding balance between curiosity-led, response-mode research, and more targeted or programmatic funding?"*

We very much welcome the *Fruits of Curiosity* project and its important goal for advancing British science through the long view. We are grateful for the opportunity to submit this brief response and to participate in the progress of the project itself.

References

1. Bush, V., As We May Think, in The Atlantic. 1945.
2. Braben, D.W., et al., UK's creative science would flourish if set free from government guidance, in Financial Times. 2009: London.
3. Campaign for Science & Engineering in the UK, *Impacts of Investment in the Science & Engineering Research Base*, in *CaSE Policy Report.* 2009, CASE: London. p. 12.
4. Iansiti, M. and R. Levien, *Strategy as Ecology.* Harvard Business Review, 2004. **82**(3): p. 68-78+126.
5. Adner, R., Match your innovation strategy to your innovation ecosystem. Harvard Business Review, 2006. **84**(4).
6. Chesbrough, H.W. and M.M. Appleyard, *Open innovation and strategy.* California Management Review, 2007. **50**(1).
7. Garnsey, E. and Y.Y. Leong, *Combining resource-based and evolutionary theory to explain theof bio-networks.* Industry and Innovation, 2008. **15**(6): p. 669-686.
8. Garnsey, E., G. Lorenzoni, and S. Ferriani, *Speciation through entrepreneurial spinoff:*

The Acorn-ARM story. Research Policy, 2008. **37**(2): p. 210-224.

9. Freeman, C., The 'National System of Innovation' in historical perspective. Camb. J. Econ., 1995. **19**(1): p. 5-24.

10. Freeman, C., Technology Policy and Economic Performance: Lesson from Japan. 1987, London: Frances Pinter.

11. Lundvall, B.-A., Innovation as an interactive process: from user-producer interaction to the national system of innovation, in Technical Change and Economic Theory, G. Dosi, et al., Editors. 1988, Frances Pinter: London.

12. Lundvall, B.-A., ed. National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. 1992, Frances Pinter: London.

13. Abramovitz, M., Catching Up, Forging Ahead, and Falling Behind. Journal of Economic History, 1986. **46**(2): p. 385-406

14. Omenn, G.S., PRESIDENTIAL ADDRESS: Grand Challenges and Great Opportunities in *Science, Technology, and Public Policy. Science, 2006.* ***314****(5806): p. 1696-1704.*

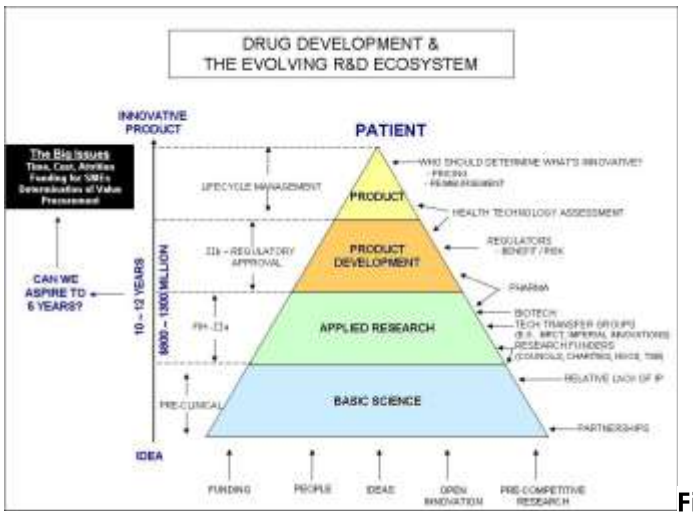


Figure 1

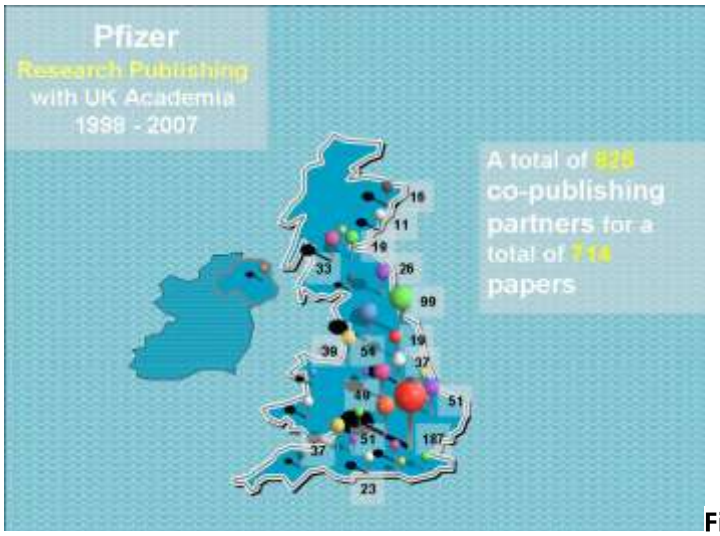


Figure 2

Research Councils UK

(RCUK)

RCUK RESPONSE TO THE ROYAL SOCIETY INQUIRY- THE FRUITS OF CURIOSITY: SCIENCE, INNOVATION AND FUTURE SOURCES OF WEALTH

Summary of Key Points

- Research Councils have a long term vision for supporting research. While the outcomes of research supported by the Research Councils can have an immediate and direct impact, the timescale for achieving full economic or societal impact is typically in the region of 10-50 years.

- All research supported by Research Councils is selected on the basis of research excellence and assessed through detailed peer review. The area of research and the ideas to be investigated are defined by researchers, either by submitting a proposal directly or by informing a Council's strategic priorities. Both approaches are often in collaboration with partners in other research groups, business, the third sector/NGOs, or the public sector.

- Research Council research funding is balanced between supporting and encouraging multidisciplinary research in themes that address major global and societal challenges and safeguarding the health of the entire research base. Investigators are closely involved in developing these themes, and in both cases have considerable freedom and autonomy in putting forward the objectives and scope of their research, and also in modifying the research as it progresses to meet new opportunities. Significant evidence shows that both streams attract the best researchers and have international impact.

- UK research plays a major role in tackling global challenges and is an essential component of the international research endeavour. Our research base generates a significant proportion of the world's research outputs, plays an important role in international science diplomacy around global issues and international development, and is a key factor in attracting leading researchers and major multinational companies to the UK. The Research Councils seek to maximise this potential by funding the highest quality, research and training, and facilitating international stakeholder involvement and networking.

- World-class facilities, data resources and infrastructure are fundamental in maintaining the UK's position as a research leading nation and attractive location for innovation. For example, the UK's new Diamond Light Source is enabling innovation across diverse and important areas ranging from energy storage technologies to drug development. Facilities are also fundamental to ensuring our participation in international research programmes, but it is unlikely that every country will be able to host the full range of facilities needed to support all research challenges. The balance between home and shared facilities will be an important dimension to UK science policy in the next 20 years.

- The UK is highly successful in obtaining EU funding. Framework Programme 6 (FP6), which ran between 2002 and 2006, supported around 2.3 billion Euros of UK research. Framework Programme 7 (FP7) will operate between 2007 and 2013, and by October 2008, UK research organisations had secured EC contributions of around 910 million Euros.

- Under FP7, the UK is involved in more funded activities than any other country, and we are second only to Germany in funding receipts from FP7. In terms of European Research Council funding, the UK has surpassed all other countries; in last year's call for advanced grants, the UK was top in hosting 21% of all projects.

Introduction

1. The seven UK Research Councils are the largest public funders of research in the UK, investing over £3 billion per annum in research, training and knowledge transfer across a broad spectrum of research areas. The seven Research Councils are:

- Arts and Humanities Research Council (AHRC)
- Biotechnology and Biological Sciences Research Council (BBSRC)
- Economic and Social Research Council (ESRC)
- Engineering and Physical Sciences Research Council (EPSRC)
- Medical Research Council (MRC)
- Natural Environment Research Council (NERC)
- Science and Technology Facilities Council (STFC)

2. Research Councils have common objectives, which are to:
   - fund the highest quality internationally competitive research;
   - support postgraduate training;
   - advance knowledge and technology, and provide trained researchers and services which meet the needs of users and beneficiaries, thereby contributing to the economic competitiveness of the UK, the effectiveness of public services and policy, health and the quality of life;
   - support public engagement with research.

3. Each Council is an independent Non-Departmental Public Body established by Royal Charter and sponsored by the Department for Business, Innovation, and Skills (BIS). The Councils are funded by BIS with an allocation from the Science Budget. Details of the funding provided for the present Spending Review period (2008-11) are available in the Science Budget Allocations published by BIS.[16]

4. The Government has responsibility for setting the over-arching strategy and framework for the research base. Within this framework, Research Councils develop their own strategies and priorities through a strong consultative process, involving leading academic researchers and representatives from industry and the public sector recognised for their knowledge of the field.

5. Each Research Council has a governing Council which acts as a senior decision making body, with members drawn from the Council's academic, business and user communities. This body is responsible for setting Research Council policy, strategy and priorities. It is also accountable for the stewardship of the Research Council's budget and the extent to which objectives have been delivered and targets have been met.

6. Each Council is supported by its own structure of high-level advisory boards and groups to identify and prioritise opportunities for research, training and knowledge transfer and to provide external advice on the development of strategies and policies.

7. Research Councils UK (RCUK) is a strategic partnership set up to champion the research, training and knowledge transfer supported by the seven UK Research Councils. RCUK was established in 2002 to enable the Councils to work together more effectively to enhance the overall impact and effectiveness of their research, training and innovation activities, contributing to the delivery of the Government's objectives for science and innovation. Further details are available at www.rcuk.ac.uk.

8. In this response, science and engineering has been interpreted to include all aspects of research, including the physical, biological, engineering, biomedical, natural and social

[16] See www.dius.gov.uk/~/media/publications/U/URN07114

science disciplines, and the arts and humanities. RCUK considers that the whole research spectrum, including the arts and humanities, is relevant to this inquiry.

9. RCUK defines innovation as the successful introduction of new services, practice, products, processes, business models and ways of working.

Support for Research

10. Research Councils have a long term vision for supporting research. While the outcomes of research supported by the Research Councils can have an immediate and direct impact, the timescale for achieving full economic or societal impact is typically in the region of 10-50 years.

11. All research supported by Research Councils is selected on the basis of research excellence and assessed through detailed peer review. The area of research and the ideas to be investigated are defined by researchers, either by submitting a proposal directly or by informing a Council's strategic priorities. Both approaches are often in collaboration with partners in other research groups, business, the third sector/NGOs, or the public sector.

12. Research Council research funding is balanced between supporting and encouraging multidisciplinary research in themes that address major global and societal challenges and safeguarding the health of the entire research base. Investigators are closely involved in developing these themes, and in both cases have considerable freedom and autonomy in putting forward the objectives and scope of their research, and also in modifying the research as it progresses to meet new opportunities. Significant evidence shows that both streams attract the best researchers and have international impact:

    - An independent study by Evidence Ltd[17] demonstrated that EPSRC's 'most successful researchers'[18] do achieve consistently impressive results based on an international comparison of the citation impact of their publications. During 2008-09 this group amounted to around 1,200 principal investigators, and analysis shows that while 68% of them were working in single-discipline fields, an impressive 58% were working in areas defined as multidisciplinary. 25% held multiple grants spanning both single and multi-disciplinary work.
    - The NERC citations study 2008,[19] which was also an independent study by Evidence Ltd, evaluated the academic impact of NERC-funded ISI journal papers published between 2003 and 2005 and showed that, whilst the rebased citations impact score for UK environmental sciences was 1.25 times world average, NERC-funded science achieved an impact score of 1.66. Within that, a comparison was made of the performances of the NERC funding modes in use at the time (responsive mode, fellowships, directed programmes and core strategic). It showed that responsive mode and directed programmes had comparable impact scores (1.93 and 1.84 respectively). Directed research included the highest proportion of most highly cited papers (those scoring > 8 times world average impact) and fellowships achieved the highest impact score of 2.03 times the world average.

International Context

13. UK research plays a major role in tackling global challenges and is an essential component of the international research endeavour. Our research base generates a significant proportion of the world's research outputs, plays an important role in international science diplomacy around global issues and international development, and is a key factor in attracting leading researchers and major multinational companies to the UK. The Research Councils seek to maximise this potential by funding the highest quality, research and training, and facilitating international stakeholder involvement and networking.

---

[17] Impact Profiles Study of EPSRC Researchers, Evidence Ltd, 2006

[18] 'Most successful researchers in this context is defined as the approximately 35% of EPSRC-funded researchers who collectively win 80% of all EPSRC research funding.

[19] See www.nerc.ac.uk/about/perform/documents/citations-study-2008.pdf

14. Training overseas researchers in the UK is one of the most important routes to international collaboration and it is vital that we maintain a strong training environment in the UK that is attractive to international researchers.

15. World-class facilities, data resources and infrastructure are fundamental in maintaining the UKs position as a research leading nation and attractive location for innovation. For example, the UK's new Diamond Light Source is enabling innovation across diverse and important areas ranging from energy storage technologies to drug development. Facilities are also fundamental to ensuring our participation in international research programmes, but it is unlikely that every country will be able to host the full range of facilities needed to support all research challenges. The balance between home and shared facilities will be an important dimension to UK science policy in the next 20 years.

16. The UK has a diverse number of elite institutions and research centres that are highly attractive to international researchers, including leading universities and institutions such as Kew Gardens, the National Physical Laboratory, the Natural History Museum, the John Innes Centre and MRC's Laboratory of Molecular Biology. These are central to maintaining and improving the reputation of the UK as an attractive arena for international investment.

17. RCUK is committed to the aims of the European Research Area (ERA). The ERA aims to create an "internal market" in research, and an area of free movement of knowledge, researchers and technology, with the aim of increasing cooperation between national programmes, stimulating competition and achieving a better allocation of resources. RCUK also values the role of the European Research Council (ERC) in complementing the research activities of national research funding agencies, and given this important role we ensure there is continuing UK involvement in the peer review of proposals. It is often our leading researchers who obtain funding from the ERC, and this funding complements their Research Council funded activities.

Evidence of the UK's International Standing

18. The UK compares favourably with the rest of the world in terms of research papers and their impact, commercialisation of research, training skilled people and the connection between the research base and policy makers. However, it is counterproductive to over-emphasise the international "league table" dimension. A useful holistic measurement of the quality of the research base is yet to be found (we are currently working closely with HEFCE to ensure both excellent research and its impact are included in the Research Excellence Framework and this may provide a more comprehensive overview, though not a single measure). However, the UK continues to make a major contribution to world research.

19. Citations statistics are commissioned annually by the Department for Business, Innovation and Skills (BIS) and provide an international comparison.[20] Key statistics for 2009 include:

    - The UK is publication-productive, with 2.26 papers per researcher. It is effectively 1st in the G8 group and well ahead of Germany (1.38), France (1.34) and the USA (1.06) where productivity is now less than half that of the UK;
    - The UK's share of world citations is rising and it now has 11.8% of world citations;
    - The UK generates 14.4% of the top 1% of most highly-cited papers;
    - The UK sustains high impact across subject areas. It remains world-leading in clinical, health, biological and environmental sciences;
    - UK internationally co-authored papers have risen from 33% in 1999 to 47% in 2007.

20. The Research Councils have commissioned several international reviews in the last 5 years which demonstrate the UK's international standing in a number of key areas. Summaries of these are provided at **Annex A**.

[20] The 2009 report will be published in October. For the 2008 report, see www.dius.gov.uk/~/media/publications/I/IntComparativePerformanceUKResearch

21. The UK is highly successful in obtaining EU funding. Framework Programme 6 (FP6), which ran between 2002 and 2006, supported around 2.3 billion Euros of UK research.[21] Framework Programme 7 (FP7) will operate between 2007 and 2013, and by October 2008, UK research organisations had secured EC contributions of around 910 million Euros.

22. Under FP7, the UK is involved in more funded activities than any other country, and we are second only to Germany in funding receipts from FP7. (This is because Germany has more partners per project, and their industry sector has a higher rate of participation – the UK is in more FP7 projects overall, but mostly academic or research institute. The work of the Research Councils European Office, UKRO, contributed significantly to achieving these successes).

23. In terms of European Research Council funding, the UK has surpassed all other countries; in last year's call for advanced grants, the UK was top in hosting 21% of all projects – France was second with 13%, Switzerland was third, and Germany was fourth.

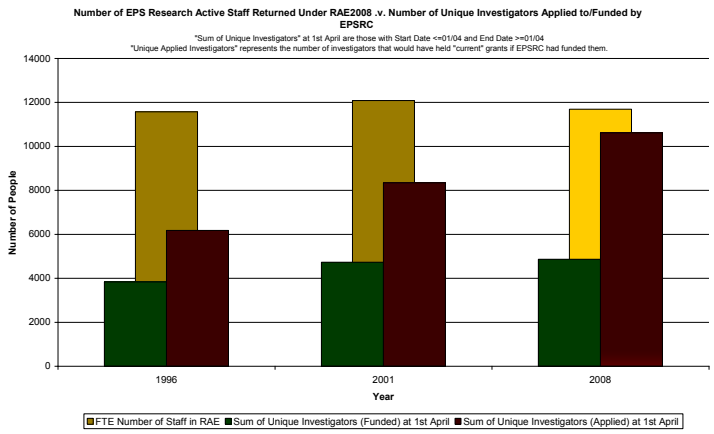
24. The Research Assessment Exercise 2008, which was based on expert review, included the views of international experts in all of the main subject areas. The results demonstrated that 54% of the research conducted by 52,400 staff submitted by 159 universities and colleges was either world-leading (17% in the highest grade) or internationally excellent (37% in the second highest grade). Taking the top three grades together (the third grade represents work of internationally recognised quality), 87% of the research activity was of international quality.

The Long-Term Direction of Policy for Science

Q1. What role should curiosity-driven research play in the UK science base in the next 15-25 years?

25. Curiosity-driven research lies at the heart of the UK research base and its success, and must continue to do so. All research supported by Research Councils is selected on the basis of research excellence and assessed through detailed peer review, and there is no difference in quality or creativity between research that is funded through different mechanisms (see paragraphs 11 and 12).

26. Competition for funds is a key factor in maintaining excellence. Reviews of competitive peer review have consistently suggested that excellence is stimulated when success rates of between 20-35% are achieved. However, the population of researchers applying to Research Councils for funding has grown significantly in the last 10 years and there is a danger that low success rates will limit the aspirations and the adventure of researchers seeking funding (see Figure 1).



[21] See ec.europa.eu/research/pdf/national-brochures-2009/eu_research_2004-2009_uk.pdf#view=fit&pagemode=none

Figure 1. Trend over time for the number of EPS staff submitted to the RAE, the number of unique investigators that applied to EPSRC for funding and the number of unique investigators who were funded.

27. Curiosity-driven research must continue to:

- allow strong, innovative ideas to flourish, and ensure the UK research community is in a position to anticipate and respond to challenges, and demonstrate excellence with impact;
- foster mould-breaking, transformative research with the potential to radically change our understanding of existing concepts or lead to the creation of new research fields;
- ensure a high quality supply of excellent researchers to respond to future challenges;
- develop visionary thought leaders who can inspire communities in new directions.

28. Given pressures on intramural R & D in global value chains, it is likely that in the future the private sector will increasingly look to the public sector for ideas, and in doing so they will seek a strong curiosity-driven research base for the co-creation and delivery of novel research ideas. Many leading companies are pursuing an open innovation agenda and there is a clear opportunity to develop further collaboration and networking as long as the quality of the publicly-funded research base is sustained.

Q2. Which elements of policy for science and innovation over the past 10 years have been successful and should be maintained? Where is there room for improvement?

29. The 10 year Science and Innovation Investment Framework (2004) and the 2006 white paper have led to a significant boost to the UK research base, particularly through the focus on:

- a long term vision;
- excellence with impact;
- the introduction of Full Economic Costing;
- sustained investment in research infrastructure;
- post-graduate and post-doctoral transferable skills training across the HE sector underpinned by 'Roberts Funding';
- the UK-wide programme for early career researchers.

30. Other successful policies include:

- Continuation of the Haldane principle;
- Formation of the European Research Council;
- Identification and implementation of RCUK priority themes;
- Public engagement with research - recognising and responding to the publics' aspirations and concerns has been an increasingly important feature in science and innovation policy in the last 10 years.[22] The Research Councils have demonstrated strong support for such an approach to decision making through a number of public dialogues (see paragraph 38);
- The formation of OSCHR - close co-ordination between MRC and NIHR(and the Devolved Administrations) facilitates more efficient translation of health research into health and economic benefits in the UK;
- Establishment of the Technology Strategy Board;
- The Energy Technologies Institute;
- The role of Foresight in informing new policies through horizon scanning and scenario setting;
- Firmer legislation to counteract the damaging effects of certain anti-vivisectionists;
- Relatively permissive legislation for human stem cell research;

[22] See CST report www.cst.gov.uk/reports/files/policy-through-dialogue/report.pdf and HE-BCI Surveys www.hefce.ac.uk/econsoc/buscom/hebci/

- A move towards greater open access to research publications.

31. RCUK considers that there is scope for more effective policy-making and implementation in the following areas:

- Planning horizons - 3-year cycles of funding are too short in all science areas. This has a particular impact on commitment to running costs of large scale capital investments which are typically over periods of more than 15 years, and long-term collaborations - for example our ability to bring long term funding to international collaborations with countries such as China, India and the US;
- The mismatch in the duration of funding for PhDs between Research Councils and Funding Councils;
- Embedding impact and interdisciplinarity within the dual support system and within HEIs - there are clear opportunities to focus on this as the Research Excellence Framework is developed;
- The increase in demand for undergraduate teaching combined with the current expectation that all teaching professors should also do research will lead to over-demand;
- Full economic costing (FEC) - this has not necessarily led to improvements in efficiency at HEIs;[23]
- The balance between the need to protect intellectual assets (for example by patenting) with the benefit of ensuring wide-spread dissemination of knowledge from the research base such that it can be exploited appropriately by industrial and other users;
- Continued development of partnerships between public funders, the commercial sector and charities and the third sector.

Q3. How will increasing support for science in the US, China and elsewhere impact on the UK's international standing and attractiveness as a place to undertake world-class science?

32. Increases in government R&D investment in competitor states may make these countries more attractive destinations for UK researchers in the future however they will also create new opportunities for stronger interactions and exchange. Given the strength of UK research, it is likely that countries with new monies will increasingly want to exploit UK expertise and the UK should be prepared to take advantage of opportunities for further collaboration, and strengthen efforts to address global challenges. Examples of this include the joint EPSRC/ National Science Foundation (NSF) sandpit on new directions in synthetic biology[24] and the NERC Rapid[25] and Rapid WATCH[26] programmes delivered with partners including the NSF, The Netherlands Organisation for Scientific Research, the Research Council of Norway and the Max Planck Institute for Meteorology, Germany.

33. RCUK has representative offices in China, USA and India which play a key role in facilitating collaboration, developing relationships with key stakeholders, influencing the international research agenda, and promoting the excellence of the UK research base. The UK Research Office (UKRO) in Brussels promotes UK participation in EU programmes (the UK academic community is the most successful in winning support from the EU Framework Programme, and is the most popular destination for EU-funded fellowships). International collaboration increases the academic impact of UK research, and we will continue to work in partnership internationally to add further value to UK strengths.

34. Further information on the international context is provided at paragraphs 13-17.

Q4. How should science be governed to maximise benefits to society while acknowledging public questions, uncertainties and concerns?

[23] See RCUK Review of the Impact of fEC on the HEI sector www.rcuk.ac.uk/review/fec/default.htm
[24] See www.epsrc.ac.uk/CallsForProposals/Archive/JointSyntheticBiology.htm
[25] See www.nerc.ac.uk/research/programmes/rapid/
[26] See www.nerc.ac.uk/research/programmes/rapidwatch/

35. The Research Councils fund research of the highest international quality, as judged by its academic standing, and require this to be carried out to strictly defined levels of integrity.[27]

36. Research Councils' ongoing engagement with the research base, government, business, the third sector and society is designed to help ensure the UK research agenda remains world leading and relevant to national and global needs. As an intrinsic part of this, we expect the research we fund to have impact and to penetrate as deeply and widely as possible, both in academic contexts and in wider society. Our underpinning rationale is that publicly-funded research is not an end in itself – society should ultimately benefit in the longer term however indirectly.

37. The benefits of research are maximised in a climate of openness and trust that enables society to have confidence in research processes and outputs. A proportionate legislative and regulatory environment is essential for this, and we believe that this is broadly the case in the UK. Research Councils recognise that broad public endorsement of the purpose and direction of publicly funded research must be earned, as part of researchers' licence to practise. Central to this is the creation of a culture in which researchers themselves value public engagement, and where their understanding of the role of science in society and their awareness of the ethical and other social issues informs their decisions throughout the lifecycle of their research.

38. RCUK's public engagement with research strategy[28] includes commitments to identify public attitudes relevant to the conduct of research, and to foster dialogue that will enable the public to contribute to Councils' policies and research strategies. The Research Councils play an active role in ensuring that public views influence and shape their own research policies through lay publics (e.g. the MRC Public Panel, a mechanism to provide patient or public perspectives) and deliberative public dialogue. Examples include:

Nanotechnology for Healthcare
The findings from a public dialogue in nanotechnology were used alongside advice from the research and user community in the development of the scope of the nanotechnology for healthcare grand challenge call. Critical to its success was the use of independent facilitators to conduct the dialogue, and the involvement of academic researchers and EPSRC staff throughout the process.

Ageing
Results from the BBSRC/MRC public consultation on ageing research[29] have helped shape the cross-Council initiative on Lifelong Health and Wellbeing, for example by ensuring that the initiative encompassed prevention research throughout life, an area identified as a priority by the public. In addition members of the MRC's Public Panel were involved in the review of applications to the Lifelong Health and Wellbeing initiative, ensuring that public concerns and priorities were reflected in decision-making.

Stem Cell Dialogue
The Stem Cell Dialogue project[30] was led by BBSRC and MRC and funded by the BIS Sciencewise initiative. The dialogue involved the largest ever public and stakeholder consultation on stem cells in the UK and included the scientific and medical communities, industry, ethics and religious groups. The findings were published in December 2008 and showed conditional support for all avenues of stem cell research, and identified issues around, for example, investment and coordination between public and private sectors, clinical trials, and communication of uncertainties.

Synthetic Biology

---

[27] See *RCUK Code of conduct and policy on the governance of good research conduct* www.rcuk.ac.uk/review/grc/default.htm
[28] RCUK Science in Society Strategy 2006 www.rcuk.ac.uk/cmsweb/downloads/rcuk/scisoc/sisstrategy.pdf
[29] Public consultation on ageing - research into public attitudes towards BBSRC and MRC-funded research on ageing www.mrc.ac.uk/Utilities/Documentrecord/index.htm?d=MRC004678
[30] See www.sciencewise-erc.org.uk/cms/stem-cell-dialogue/

On behalf of the Research Councils, BBSRC and EPSRC are leading on a programme to develop effective public engagement around synthetic biology. A public dialogue, part-funded by Sciencewise, is expected to address topics such as regulatory, ethical and other social issues.

Geoengineering
With the support of the Royal Society, which launched the report *Geoengineering the Climate*[31] on 1 September 2009, NERC has applied for Sciencewise support to run a public dialogue exercise on the issues of public concern around different geoengineering options and the need for, and direction of, research in this area. EPRSC and ESRC will be engaged in this activity as well as the Royal Society and members of the engineering community.

39. The Research Councils expect their grant holders to demonstrate awareness of the social and ethical implications of their research, beyond usual research conduct considerations (including identifying issues that require public debate and/or new regulation, e.g. human fertilisation and embryology), and engage actively with the public.[17] The Research Councils provide training, rewards and support in this regard.

40. RCUK, with the UK Funding Councils and the Wellcome Trust, funds a £9.2million Beacons for Public Engagement initiative to help secure a step change in the way public engagement is recognised and rewarded and to encourage culture change within universities.

Q5. How should we assess the long-term social and cultural impacts of scientific research?

41. Methodologically, measuring the long-term social and cultural impacts of research is difficult. Robust techniques need to be developed to assess social and cultural impacts, recognising the high diversity and non-linear nature of such impacts and the largely unpredictable timeframes. Organisations need to work together to assess the impact of a portfolio of research as a whole rather than seeking to assess each project or organisation individually.

42. Despite these difficulties, the Research Councils recognise that publicly funded research should benefit the UK culturally, socially (including politically) and financially, and have clearly set out these expectations from the research community in a statement published in July 2008.[32]

43. Examples of social and cultural impacts of research can be found in the recently published RCUK publication *Impacts: Success in shaping public policy and services.*[33] This provides a variety of case studies highlighting how Research Council funded research provides evidence to inform policy making in the UK on issues such as the future energy landscape, returning to employment, and health.

44. Researchers undertaking a recent study for the MRC, the Wellcome Trust and the Academy of Medical Sciences had to develop a methodology to calculate the health and economic gains from investments in specific areas of research. The study, entitled *Medical Research: What's it worth,*[34] focused on cardiovascular disease and mental health research and estimated that that the health and GDP gains derived from UK public and charitable investments in these areas (specifically over the period 1975–92) would be equivalent to an annual rate of return of around 39% (37% for mental health research). The time lag between research expenditure and eventual health benefits in these areas was estimated to be around 17 years.

45. Effective public engagement also facilitates the social and cultural impacts of research. RCUK has recently commissioned research into the benefits of public engagement of research for researchers and research. The report is due in the near future and will be provided to the working group separately.

[31] See royalsociety.org/displaypagedoc.asp?id=35110
[32] See www.rcuk.ac.uk/cmsweb/downloads/rcuk/innovation/expectationssei.pdf
[33] See www.rcuk.ac.uk/cmsweb/downloads/rcuk/publications/impactspps.pdf
[34] See *Medical Research: What's it worth* available at www.wellcome.ac.uk/About-us/Publications/Reports/Biomedical-science/WTX052113.htm

46. The movement of trained researchers is an important impact of research, giving researchers the skills and knowledge to move into careers in policy and practice, providing high level skills for the economy and spreading ideas and expertise. The Research Councils offer opportunities for academic placements with Government or industry partners, allowing researchers to spend time working directly with a partner organisation and to take a direct role in the development of policy or business practice.

47. Research Councils are encouraging applicants to start thinking about the potential impact of their research at the earliest stages of the application process, with the introduction of impact plans. The Research Councils are also arguing strongly for the explicit assessment of impact (widely interpreted) to be a formal requirement within HEIs through its inclusion in the Research Excellence Framework. Research Councils recognise a wide range of potential impacts, including the impact of skilled people, technology and policy development, wealth creation, and quality of life improvements.

Investing in Tomorrow's Talent in Schools, Universities and in the FE Sector

Q6. How much progress has there been in the past decade in the delivery, content and assessment of education in STEM (Science, Technology, Engineering and Maths) subjects?

48. The Research Councils continue to inform UK schools policy development through the important research they fund in this area, in particular through ESRC major investments – for example the Teaching and Learning Research Programme[35] and the Science and Maths programme[36]. The ongoing work of the DCSF/BIS 5-19 STEM programme board – set up to improve STEM subject delivery in England – has been informed by research outputs from these and similar programmes, and it is important that links between policy development and research in this area are maintained. A list of relevant findings from ESRC research that informs this area is provided at **Annex B**.

49. The action plans emerging from the DCSF/BIS 5-19 STEM programme have helped to clarify the needs of schools to providers and funders of learning enrichment. In recent years the RCUK approach to funding work with schools[37] has developed in important new areas that reflect these needs, e.g. involving researchers in the development and delivery of teacher CPD[38] and curriculum development, as well as the more traditional classroom placement. There is scope for further development in this area.

50. The Research Councils are also developing the links between working with schools and researcher skills development – this is potentially a powerful mechanism for embedding working with schools as an everyday part of research career development.

Q7. What are the future challenges for STEM education at primary, secondary and tertiary levels? How should these challenges be addressed?

51. While the Research Councils do not have formal responsibilities in these areas, it is clear that a) student exposure to practical work in STEM and b) maths skills being taught for longer[39] as an integral part of all STEM (including social science), are notable deficits in this area. These have an adverse impact on the quality of young people's education and their experience of it, and on the extent to which we can expect our future research workforce to be skilled.

52. Research is becoming more interdisciplinary in nature, and this needs to be more fully reflected in STEM education, for example, how natural phenomena need to be understood

[35] See www.tlrp.org/
[36] See www.esrcsocietytoday.ac.uk/ESRCInfoCentre/opportunities/current_funding_opportunities/science.aspx
[37] i.e. directly supporting researchers to work with schools as opposed to funding research in this area.
[38] See www.rcuk.ac.uk/sis/linksci.htm
[39] BBSRC in particular are currently seeking ways of addressing this issue.

using an integrative approach drawing on a variety of scientific perspectives, or how techniques developed in one area may be successfully transferred to another. Although this is becoming more widely recognised – for example the core content of the new Science Diploma has links with the RCUK multidisciplinary Grand Challenges – it is unclear whether or how much teaching at secondary and tertiary levels is adapting to these needs.

53. The range of issues surrounding the supply and demand for STEM skills is well documented, for example in the 2009 summary from BIS.[40] The recently launched HE STEM programme at Birmingham University is set to address issues surrounding widening participation and increasing the number of students graduating from STEM courses in England and Wales. There may be opportunities to further explore sector-wide approaches among relevant BIS Science and Society Expert Groups.

54. Effective and persuasive STEM careers guidance is a vital part of secondary and tertiary education if sufficient numbers of young people are to be attracted into scientific research. Much is currently in development with DCSF at secondary level, but a more combined approach to careers guidance that is effective and supportive of young people across all stages of education should be developed.

Q8. How do we ensure that adequately qualified science and mathematics specialists are attracted into the teaching profession at all levels of education (primary through to tertiary)?

55. Increasing the proportion of STEM secondary teachers with high quality STEM-specific qualifications or research experience in their specialist area seems likely to require a shift in the way that those possessing these qualifications perceive teaching as a career. The benefits (qualitative as well as monetary) of moving into teaching need to be competitive with other STEM careers to offer a real incentive.
56. Programmes such as INSPIRE[41] at Imperial – where students are involved in teacher training alongside their STEM PhD research - can illustrate the benefits of combining research and teacher training.
57. Programmes such as RCUK Researchers in Residence[42] run placements that put young researchers into schools environments, from where participants are shown to have become interested in or motivated to pursue a career in teaching.[43]

Building and Sustaining Research Careers

Q9. How can we make research careers – within academia or industry – a more attractive option for young people, both within the UK system and from abroad?

58. The recent report for BIS, entitled *Research Careers in the UK: A Review*[44] by Professor Nigel Thrift, answered a very similar question: ''It has been suggested that there is a perception that doctoral, post-doctoral and subsequent stages of typical research careers are increasingly been seen as not very attractive to graduates compared to other possible careers. How can this issue be tackled?''

59. The review noted that ''researchers form a fundamental element of the supply of skills which will be required if the UK is to maintain its leading position in the world'' and stated that ''the UK government is concerned that research careers are not always perceived as attractive by the best graduates. This review seeks to establish whether this is the case and, if so, why the situation exists and what can be done to improve matters.''

---

[40] See www.dius.gov.uk/~/media/publications/D/Demand_for_STEM_Skills
[41] See www3.imperial.ac.uk/inspire
[42] See www.researchersinresidence.ac.uk/
[43] Researchers in Residence Annual Reports
[44] See www.dius.gov.uk/higher_education/shape_and_structure/he_debate/~/media/publications/N/Nigel%20Thrift%20contribution%20to%20HE%20Debate

60. The review concluded that: "The message of the review is straightforward. Many initiatives are currently either in place or being put in place but they need stitching together and supplementing in order to provide coherent policy that covers all stages of the research career. For the health of the UK research base 15 years from now, it is imperative that this process is started."

61. One of the aims of the RCUK Research Careers and Diversity Strategy is to ensure the best potential researchers are attracted into research careers. We need to improve understanding of the diversity of the recruitment pool and early career researcher population, and raise awareness of research careers. RCUK is working with Vitae on the marketing of researcher development programmes.

62. The Royal Society report entitled *Hidden Wealth: the contribution of science to service sector innovation* highlighted that ongoing attention to the supply of knowledge and skills must be central to the innovation agenda if success is to be ensured.

Q10. What sorts of incentives can we develop to keep talented students and postgraduates in science?

63. There are a number of initiatives already in place. BBSRC and EPSRC fund vacation bursaries, and other organisations such as the Nuffield Foundation provide similar opportunities. EPSRC has recently piloted 'PhD Plus', where universities provide up to 1 year of additional funding for their best PhD students, to help them launch a successful research career. RCUK is exploring how more could be done in partnership with other organisations.

64. Evidence from surveys such as the Postgraduate Research Experience Survey (PRES) and the Careers in Research Online Survey (CROS), and research reports, note that a supportive culture and environment within the sector with clear career paths and development opportunities together with monetary reward are important to researchers.

65. The UK needs to keep more talented scientists within industry, academia and Government. We need to create a climate where industry wishes to invest more in research, where there is more collaboration between industry and HEIs (including greater freedom of movement of people) and where dynamic, young science entrepreneurs can more readily form their own companies. An example of this is the Industrial Doctorate scheme, where students spend 75% of their time working in industry, and also develop entrepreneurial and business skills.[45]

Q11. Does the standard career-track model need to be re-evaluated? Should we take more account of the movement of skilled individuals between academia, industry and business?

66. Research Councils are developing and populating a career stories portal and database (through Vitae) and a framework to support the career development of researchers, as recommended by the Council for Science and Technology (CST) report *Pathways to the Future*. The movement of researchers is a positive aspect of training and can be for short learning experiences, longer exchanges or permanent employment.

67. RCUK encourages collaboration and exchanges with industry at an early stage through CASE (or similar) awards and early-stage research grants, and throughout careers through Industrial Fellowships, jointly funding Chairs and people exchange schemes.

68. ESRC offers placement fellows schemes which enable social science researchers to spend time in a business organisation or government department to carry out a project or, in reverse, for a member of a business organisation or government department to work on a project that is relevant to their organisation in a setting where they have access to academic resources. MRC supports a similar two way exchange programme between academia and industry while NERC offers similar placements within the public sector.

[45] See www.epsrc.ac.uk/PostgraduateTraining/Centres/IDCs.htm

69. There are still significant disincentives to short-term transfers between academia and industry and the UK needs to address the cultural barriers that are preventing a natural flow between the two throughout a research career. Compared to the US, we have a greater movement of PhD students but fewer exchanges of career researchers. The Royal Society could play an influential role in working with the Research Councils to find ways to recognise such transfers as a valid and important part of the career path in both public and private sectors, and to decrease the barriers.

70. Experience and exchanges in public engagement, policy-making and internationally are also important opportunities for career development. RCUK is working with Universities UK to look at how these aspects of experience are considered in academic promotion criteria.

71. A research synthesis was commissioned by ESRC and the Research Councils UK Research Careers and Diversity Unit to look at PhD graduates' career choices and impact.[46] A key finding was that PhD graduates are found across the full range of professions and sectors, with low levels of unemployment and high employability over time. Furthermore, the majority of PhD graduates are generally satisfied with the careers they are in, and wish to stay in their respective field. Growing numbers of international and part time people are studying for doctorates including increasing numbers of experienced professionals returning to study. In some specific areas of employment, such as Research and Development, PhD graduates are seen to bring competitive advantage and invaluable knowledge and connections.

Science, Innovation and Wealth Creation

Q12. How can we strengthen science and innovation in all parts of the private sector in the UK, and further improve the exchange of knowledge and expertise between the public and private sectors?

72. Science and innovation in the private sector is strengthened by a strong publicly funded research base with behaviours and mechanisms which support collaboration, and information and people flow. Examples of collaboration are provided at **Annex C**. Some 2,300 user organisations collaborated on EPSRC research grants during 2008-09, and around 1400 PhD students were engaged on collaborative training projects. Malcolm Skingle, GSK, considers that "one of the unique selling points of the UK is you can pick up the phone to the Research Council to articulate industry needs and very quickly do great things together to address the issue."[47]

73. The introduction of impact plans for grant applications encourages researchers to consider the wider potential impacts of their research in relation to users at the earliest stage in the formulation of their research proposal. The RCUK Statement of Expectation for Societal and Economic Impact highlighted previously outlines the responsibilities of grant holders to ensure impact from their research.

74. The Research Councils support knowledge exchange through a number of schemes targeted at areas such as collaborative R&D and people exchange. All activities can be found on the RCUK Knowledge Transfer Portal.[48]

75. As well as supporting collaboration with academics, Research Councils build partnerships with key research users across business, public and third sectors, and involve them in strategy development and peer review.

76. Recent research funded by ESRC shows that many R&D-intensive and science-based businesses choose to locate in science parks which aim to support and promote transfer

[46] See www.esrcsocietytoday.ac.uk/ESRCInfoCentre/Images/One%20page%20summary%20-%20Career%20Choices%20and%20Impact%20on%20UK%20Graduates_tcm6-30436.pdf
[47] See www.epsrc.ac.uk/CMSWeb/Downloads/Publications/Pioneer/PioneerIssue01.pdf
[48] See www.rcuk.ac.uk/innovation/ktportal

among innovative organisations.[49] STFC is developing the laboratory sites at Daresbury and Harwell as National Science and Innovation Campuses. They combine our skills and facilities with the knowledge of HEIs and support from the private sector and will further enable knowledge exchange. The Campuses strongly rely on open innovation to drive both science and wealth creation.

77. As mentioned previously, it is widely recognised that the movement of skilled people is one of the most effective ways of ensuring knowledge exchange and so it is vital to address the cultural barriers to transfers between academia and business.

78. The support and recognition of knowledge exchange as a discipline is required to develop a generation of technical experts operating at the interface between research and the users of research. This is a translation role and also requires the presence of networks and champions within both communities. Within the HEI community, this is an extension of the excellent progress made in developing technology transfer offices over the last two decades into looking more broadly at impact.

79. By working closely in partnership with the Technology Strategy Board, all Research Councils increase UK business access to the knowledge base. The Research Councils are committing over £120M collectively to this collaboration over the spending review period and also add value in ways that cannot be measured by financial targets, by ensuring strategic alignment between the research base and UK needs. Recent activities are highlighted at **Annex D**.

Q13. How can we improve the scale and contribution of private sector R&D?

80. Research Council partnerships with key research users encourage co-funding of research, leading to major new investments - examples are provided at **Annex C**. The private sector also recognises the role of the Research Councils in investing in key skills; the 2007 User Satisfaction Survey conducted by PricewaterhouseCoopers for RCUK showed that 88% of users surveyed agreed or strongly agreed that the Research Councils are dedicated to investing in research skills.[50] There have already been noticeable improvements in the contribution of private sector R&D; for example over £201 million in resources was committed by business and other users in support of new EPSRC research grants (a significant increase on the £90million committed by users in 2007/8).

81. The scale and contribution of private sector R&D varies across different industrial sectors. Emphasis should be placed on those sectors which historically have not been particularly research active, for example agri-food and finance, and ensuring that there is greater engagement with the research base in these areas. Progress is being made for example in the following areas:

- BBSRC is increasing its engagement with the agri-food sector, particularly through the Diet and Health Research Industry Club, which now involves 15 major companies;
- MRC's Pharma forum, established in 2008/09, provides a platform for continuing and effective engagement between the MRC and the pharmaceutical/biopharmacology sectors, consolidating links and supporting strategic interactions. The MRC is also working with industry to develop programmes such as the MRC Industrial Collaborative Awards which simplify collaboration;
- NERC and EPSRC are working with the financial services sector, through co-sponsorship of knowledge transfer partnerships undertaking research into risks associated with natural hazards, and supporting financial mathematics research collaborations.

82. For sectors that invest heavily in R&D, we need to work with key partners to ensure stronger alignment between their investment and research council portfolios to ensure that industry is accessing the best research – for example Rolls-Royce have a number of research

[49] See www.esrcsocietytoday.ac.uk/ESRCInfoCentre/Plain_English_Summaries/work_organisation/innovation_change/RES-171-22-0001.aspx
[50] See www.rcuk.ac.uk/cmsweb/downloads/rcuk/economicimpact/ussurvey.pdf

partnerships that coincide with EPSRC research spend, such as the University Gas Turbine Partnership at the University of Cambridge.[51]

Q14. What initiatives (e.g. tax credits) have been successful or not with regards to supporting innovative businesses in the UK? How can the UK better support business?

83. As noted in paragraph 79, the Research Councils work closely with the Technology Strategy Board to support UK business, and recent activities are highlighted at **Annex D**.

84. The Research Councils also support business by providing research evidence on business practice and innovation policy. The Innovation Research Centre, funded by ESRC, BIS, NESTA and the Technology Strategy Board, will advance knowledge on how to create and sustain innovative businesses. The Advanced Institute of Management, funded by ESRC and EPSRC brings academics together with business, the public sector and policy thinkers in order to develop and deliver research of a world class standard which has an immediate and significant impact on management practice.

85. The Small Business Research Initiative (SBRI) has been operating since 2001 and has been successful in supporting Small and Medium-sized Enterprises (SMEs). SBRI brings innovative solutions to specific public sector needs, by engaging a broad range of companies in competitions for ideas that result in short-term development contracts. The Research Councils are not currently involved in this scheme.

The Ecology of Research Funding

Q15. How do we maintain an appropriate funding balance between curiosity-led, response-mode research, and more targeted or programmatic funding?

86. As highlighted in paragraph 11, all research supported by Research Councils is selected on the basis of research excellence and assessed through detailed peer review. The area of research and the ideas to be investigated are defined by researchers, either by submitting a proposal directly or by informing a Council's strategic priorities. A more important question is how to ensure the right balance of funding between supporting and encouraging multidisciplinary research around major themes and global challenges and supporting a healthy research base. As demonstrated in paragraph 12, both streams attract the best researchers and have international impact.

87. Research Councils develop their funding priorities through a strong consultative process involving leading academic researchers and representatives from industry and the public sector recognised for their knowledge of the field, as highlighted in paragraph 4. It is worth noting that 63% of Council Members (62 out of 99) across all Research Councils are Fellows of Learned Societies.

Q16. What would an ideal research funding landscape look like in 20 years time? How would funding be allocated? What would the funding bodies look like? How would they relate to one another?

88. The Research Councils' vision is for a vibrant UK research base, recognised as one of the best environments in the world to do research and PhD training. A broad base of research would be supported by additional investment in key priority areas, maintaining our internationally competitive position. There would be a strong pattern of open innovation collaborations across a variety of sectors, and UK researchers would have a strong commitment to excellent research with impact.

89. We envisage that the basic structure and principles around the current dual support system would exist, but there would be better alignment across the two halves. It would be highly beneficial to align the capabilities offered by HEIs (infrastructure, skill sets) and the strategic goals of the Research Councils (such as interdisciplinarity, impact and public engagement).

[51] See www-g.eng.cam.ac.uk/ugtp/upublic/ugtpintro.html

90. The international landscape would require national organisations to collaborate internationally. There would be increased co-funding with overseas counterparts, including international facility developments.

91. An essential component of the funding landscape would be a greater multiplicity of funding sources, including a stronger philanthropic contribution to research in all areas. This would provide more opportunities to researchers, and more competition between funders to fund the best research and offer the best training programmes. It would also give breadth to the research supported in the UK and ensure capability in key areas.

92. The outcomes from the research base should be afforded far greater importance than the structures in place across the research landscape. There are many possible alternative structures for the Research Councils, but these would not necessarily lead to any significant improvements. In the USA there are just two main Research Council analogues (the National Science Foundation and the National Institutes of Health); despite much effective cooperation there are still some difficulties in funding research between directorates in the National Science Foundation. There have been many successful outcomes from multidisciplinary research programmes funded by the Research Councils, including from the six current cross-Council priority theme areas, and examples can be found in the RCUK publication *A Winning Blend*.[52] We recognise, however, that there is still work to be done to improve the confidence of the research community in how Research Councils can jointly fund projects effectively.

93. It would also be useful to open the debate on the ideal structures within universities (for example their potential organisation around societal challenges or multidisciplinary research areas) and identify effective drivers for, or barriers to, changes within their structure.

Q17. What role should public sector R&D outside the ring-fenced science budget (e.g. departmental spending, government procurement and national laboratories) play in supporting the UK science base?

94. Public sector R&D outside the ring-fenced science budget should in general be complementary to that within the ring fence, and be coordinated around cross-government research priorities. This is an important part of the funding landscape and partnerships have been established to maximise its effectiveness, such as Living with Environmental Change (LWEC), the Environment Research Funders' Forum (ERFF), OSCHR and the UK Collaborative on Development Sciences (UKCDS). Government-funded programmes targeted at specific sectors such as the Technology Strategy Board which supports the commercial sector are also important.

95. There is still a lack of joined up governance for public sector R&D funding in the UK. The primary criterion for government department funded research, which is largely managed through commissioning, is strategic need, rather than excellence as expressed through the peer review system. This can have an impact on the quality of the research, and potentially the impact that can be achieved for the benefit of the UK and more widely.

RCUK, September 2009

Annex A - Research Council International Reviews

Chemistry (2009) - The panel found the overall health of chemistry research in the UK to be good, with significant changes in research emphasis since the last International Review. They observed pockets of truly outstanding (world-leading and world-class) work going on and numerous examples of very well-supported research groups. The panel found that top-level research is not confined to just one location, and saw excellent examples of international

[52] See www.rcuk.ac.uk/cmsweb/downloads/rcuk/documents/winningblend.pdf

collaboration, especially via EU programmes and a number of good examples of cooperation with industry. Multi-disciplinary research efforts are expanding, with specific pockets of excellence being nucleated via Doctoral Training Centres (DTCs). The panel was impressed with the calibre and intellectual strength of some of the early career scientists they met, and felt that UK Chemists are better prepared than in the past to tackle society's challenges. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/ChemistryIR2009.pdf.

Materials (2008) - The general health of the UK materials research programme was judged to be good, with an impressive number of research leaders of international stature (considering the size of the scientific community), and a body of younger faculty that is fully competitive on the international stage. The Panel was impressed by the closeness and extent of industrial collaboration when compared to international standards, and was pleasantly surprised to discover, in contrast to some countries (including the US), that IP rights are seldom barriers to industry-university cooperation. Citing the recent decision by a multinational materials manufacturer to use a UK university as its research partner the panel noted that the quality of UK academia and their access to excellent facilities, including ISIS and DIAMOND, contribute visibly to the international competitiveness of the UK. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/MaterialsInternationalReview2008.pdf

Physics (2008) - The Panel concluded that physics research in the UK is in a generally good state of health, with departments performing curiosity-driven research of the highest international quality and having benefited from a significant increase in research expenditure in recent years. The Panel also concluded that UK physics research is performing strongly, and this is reinforced by the UK's strong performance in research outputs. In their high-level analysis of the international quality of UK physics research the Panel concurred with the findings of the 2005 International Review of Physics and Astronomy, and the relevant sections of the 2008 International Review of Materials Research. See http://www.rcuk.ac.uk/cmsweb/downloads/rcuk/reviews/physics/review.pdf.

UK Light Sources Review (2008) - In general, the international committee was very impressed by the standard and leadership of UK light source science. The SRS (which closed in 2008) has played an important historical role in the growth of synchrotron radiation science. The UK has been a major player in the outstanding success of the European Synchrotron Research Facility. The Diamond light source is an exemplar of the possibilities for new 3rd generation sources, and the UK community is poised to benefit from this well-built new source. See http://www.scitech.ac.uk/resources/pdf/UKLSRReport.pdf.

Economics (2008) - The Panel concluded that the overall quality of UK Economics research is exceptional and second only to the USA internationally. It identified the UK is as the world-leader in micro-econometrics with very significant strengths in development economics, industrial organisation, international trade, labour economics, public economics and economic geography. The report also highlighted the impressive amount of high quality applied work in the UK, and the important contribution that economists make to government policy. See http://www.esrc.ac.uk/ESRCInfoCentre/Images/Economics%20IBR%20Report_tcm6-29591.pdf.

Politics and International Studies (2007) - The Panel found considerable evidence of research quality across almost all the principal sub-disciplines and identified the UK as a world leader in several important areas (including political theory, electoral studies, the 'English School' of international relations, EU studies, 'critical' security studies, political economy, certain areas of public policy and administration, and comparative and area studies). See http://www.esrcsocietytoday.esrc.ac.uk/ESRCInfoCentre/Images/P_IBR-Final_Report_tcm6-23426.pdf.

Social Anthropology (2006) - The Panel was very impressed by the quality of UK Social Anthropology, describing the UK as one of the discipline's intellectual heartlands and assessing it as a world leader in a large number of many research areas. See http://www.esrc.ac.uk/ESRCInfoCentre/Images/Ant_Book_A-web_tcm6-16599.pdf.

ICT (2006) - The Panel was impressed with the breadth and quality of ICT research throughout the UK, and noted that there had been significant improvements in ICT research and attitudes since the previous review in 2001. The community was felt to be doing exciting, high quality, world class research across a wide spectrum. Morale perceived to be high, and the excitement of institutions and individuals at each of the week's events was described as refreshing and contagious. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/ICTIntReviewReportV2.pdf.

HPC (2005) - The Panel found that research using HPC in many areas is of the highest standing and competitive at the international level. However, in a dynamically changing and rapidly evolving field such as CSE, one cannot afford to stand still, and therefore in this report the Review Panel also point out areas for further improvements and refinements of the HPC research strategy. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/HPCInternationalReviewReport.pdf.

Physics/Astronomy (2005)- The Panel noted that the UK continued to enjoy a high standing in astrophysics and solar system physics, with the best departments and individuals having outstanding international reputations. See http://www.ioppublishing.com/activity/policy/Projects/International_Review/index.html.

Engineering (2004) - The Panel judged more than two thirds of the groups they saw to be world-class or better, with notable strengths in areas such as: acoustics, bio-engineering, controls and systems and mechanical engineering. However, responses by international researchers to a questionnaire suggested that UK engineering research had been losing ground compared to other countries for about a decade. The panel also noted relatively little interaction between engineering and basic science, particularly with respect to building on the latest scientific discoveries. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Publications/Other/InternationalReviewReportEng.pdf.

Operational Research (2004) - The panel noted that the UK is recognised and respected internationally as the birthplace of Operational Research. The UK community is internationally visible through publications in a wide range of international journals, and has strong interactions with the other OR research communities throughout the world. The UK community was judged to be in a leading position in areas such as: mathematical programming (including linear and non-linear programming, integer and combinatorial optimisation and stochastic programming), stochastic modelling, scheduling, performance analysis, development and application of heuristics, simulation and financial engineering. See http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/OpResReview.pdf.

Annex B - ESRC Research on STEM Education

Relevant research has been supported in STEM education under the following ESRC co-funded initiatives:

Teaching and Learning Research Programme – Findings from TLRP show that learning and teaching methods, the curriculum and assessment are all highly influential in the formation of student attitudes towards science, as is the quality of the teaching they receive. There is strong empirical evidence that some of the fundamental concepts on which scientific understanding is built are commonly misunderstood by learners, and materials have been developed for teachers to assist them in planning how to tackle difficult content in a way that their students understand. Furthermore, research has shown that, for teaching to be effective in promoting learning, it must involve interaction between teachers and students – one-way delivery from a teacher does not work for the vast majority of pupils.
Further details on TLRP findings in this area are available at http://gtcni.openrepository.com/gtcni/bitstream/2428/47937/1/TLRP_Science_Commentary_FINAL.pdf

Targeted Initiative in Science and Mathematics Education - The overall aims of this initiative are to support the development of research–informed policy and practice with the potential to

make a significant contribution to ensuring that future generations have the mathematical and scientific skills required by the UK as a competitive knowledge economy, that there is a flow of highly skilled graduates for future research, teaching, business and other careers requiring such skills, and that future citizens have the capacity to engage more fully in debates about, and to benefit from, science and technology. Projects are still in the early stages, so have yet to report significant findings, but initial findings from research into the major changes in the science curriculum for 14-16 year olds since 2006 suggest that many teachers are finding the reformed courses an opportunity to respond more effectively to the varying needs of different pupils. However, other teachers are concerned that courses focusing on the goals of scientific literacy are often insufficiently challenging for highly attaining pupils.

Technology Enhanced Learning Programme – Funded jointly by ESRC and EPSRC, this programme comprises eight interdisciplinary projects focussed upon the creation, development and exploitation of digital technologies for learning through a better understanding of their capability to transform the quality of learning experiences and lead to enhancements in learning outcomes. Again, projects are still at a fairly early stage, but initial findings are showing that the use of transformative technologies, whilst they have the power to make some aspects of STEM subjects more accessible and engaging, they do involve a substantial investment of time and energy, as well as subject knowledge on the part of the teacher.

Annex C – Collaboration with Private Sector and Other Users and Funders of Research

The Research Councils engage with the private sector and other users and funders of research in many ways, from involvement in strategic boards to co-funding of research projects. The following examples provide a flavour of the breadth and scale of interactions, all of which help strengthen science and innovation across the UK and improve knowledge exchange.

AHRC

- Fighting crime through more effective design: Designing new products aimed at to preventing bag theft from restaurants and bars. JD Wetherspoon contributed £20,000 to this collaborative project to fund the testing of the clips in their bars.
- 3-D Computer Arts in Clinical Radiology. This project involved collaboration with the Department of Clinical Radiology at Ninewells Hospital in Dundee and the Health Service Research Group at The Robert Gordon University in Aberdeen to explore how 3-D digital images could enhance medical scans and help patients understand more about their disease.

BBSRC

- Around one third of the membership of BBSRC's senior decision making groups (Council, Boards and Panels) are users drawn from industry, government, and practitioners
- Since 2005, BBSRC's investment in collaborative research has more than doubled, with new commitment accounting for a significant proportion of this.
- One of BBSRC's main mechanisms for the support of collaborative R&D is the Research & Technology Club (RTC): during 2008-09 awards were made in bioprocessing (through the Bioprocessing Research Industry Club) and diet and health (through the Diet and Health Research Industry Club), and applications were sought for research in biorefining (through the Integrated Biorefineries Club); in total 43 companies are involved in the three clubs

EPSRC

- Some 2,300 user organisations collaborated on EPSRC research grants during 2008-09, and around 1400 PhD students were engaged on collaborative training projects; over £201 million in resources was committed by business and other users in support of new research grants (a significant increase on the £90million committed by users in 2007/8).
- Around one third of the membership of EPSRC's senior decision making groups (Council, Boards and Panels) are users drawn from industry and government.
- A specific example of the public and private sectors working together on research is the 'SAMULET' project launched in July this year. This is a collaborative programme to that aims to accelerate the development and introduction of low carbon aircraft engine

technology and to strengthen the supply chain for the UK's aero-engine industry. It is being led by Rolls-Royce working in a consortium alongside other high profile manufacturers, SMEs and several of the UK's top universities. EPSRC is investing £11.5m and the Technology Strategy Board £28.5m in the programme. Further support is under discussion with regional bodies, and total project value including industry investment is expected to be around £90m.

ESRC

- Business Placement fellows Scheme: in 2008/09, 5 business representatives were placed in an academic unit through this scheme.
- Business seminars and workshops: in 2008/9 events have included a number of Business Engagement Forums, bringing together members of the business community from priority sectors identified in the ESRC's Business Engagement Strategy. Forums have been held with the creative industries, financial services and the retail sector. Other business events have been held with a range of partners, including the Association of Chartered Certified Accountants (ACCA) and the Institute for Small Business and Entrepreneurship (ISBE).
- ESRC has commissioned four capacity building clusters in business research and engagement.

MRC

- NHS service support costs: Cost sharing agreement for MRC funded research undertaken within the NHS or involving NHS patients. Direct research costs are met by the MRC whilst the NHS would meet any associated patient care costs that may be involved. The formal agreement which outlines the terms of the partnership also specifies the circumstances under which the NHS will support non-commercial externally funded research and development by meeting legitimate associated patient care costs.
- MRC inward investment successes reported for 2007/8 include:
  - External income from the private sector to MRC Units and Institutes rose above £30m in 2007/08.
  - MRC Development Gap Fund projects have generated over £6m of new investment, been involved in the formation of two new companies, and created 44 skilled jobs.

NERC

- For environmental science, impact on policy-making is crucial to benefitting society and the economy. Engagement of policymakers in the co-design and co-funding of research programmes maximises impact and ensures it is embedded in the research which is carried out. As an example, in 2009, a £45m NERC programme of research leveraged £40m from partner organisations, enabling more science with greater impact.
- The Ocean Margins (LINK) multidisciplinary programme ran from 2000 to 2007 and was jointly funded by NERC, the UK Government and UK industry to encourage collaboration and partnership between the UK science base and industry. EPSRC also contributed funding to projects within a specific theme. The Programme aimed to improve geological understanding of ocean margins. The Programme Management Committee included representatives from Statoil (UK) Ltd and BP Oil Exploration Operating Co Ltd. NERC allocated £4.8m to the programme, which supported 15 NERC studentships, 3 industry studentships and 1 NERC fellowship
- The Willis Research Network (an environmental science-focussed research programme established by re-insurance brokers Willis Re) invests in UK science because, uniquely, the breadth and depth required for their catastrophe and risk modelling exists in one country and can be brought together to meet their business needs.

STFC

- National Science and Innovation Campuses - the STFC has considerable linkages with other research councils, public services and businesses through its both facilities and grants programmes. It aims to increase this interaction over the next 20 years through the development of its Science and Innovation Campus based at Daresbury (DSIC) and at Harwell (HSIC). Both Campuses are public-private sector joint ventures. HSIC is already home to more than 120 organisations including the STFC Rutherford Appleton Laboratory, Medical Research Council and Health Protection Agency. It has also been

announced as the site of the European Space Agency's UK Centre. The first phase of the Daresbury Science and Innovation Campus has included development of the Cockcroft Institute for Accelerator Science and the Daresbury Innovation Centre for new businesses, which is already over capacity as home to more than 80 new businesses, including a number of STFC spin-outs.

- STFC Innovations Ltd (formally CLIK) has been launched with the expressed aim of developing further Knowledge Exchange and product development to ensure that ideas originating from STFC laboratories are taken into the UK and global market places. By inviting investment from private individuals and industry, a number of successful spin-out companies covering industries such as health, technology and security have been created.
- Industrial interaction with the STFC's research groups and facilities is a vital stimulant to innovation, with both sides gaining from the relationship. The Council's unique position as one of the largest multidisciplinary research organisations in Europe means that industry and academia are assisted in a number of ways, including: Knowledge Transfer Schemes from CERN and ESA; Innovations Partnership Scheme to Industry; Facility Access for industrial users; Knowledge, Innovation, Technology Enterprise (KITE) schemes – fellowships and placements; and significant commercial contract opportunities.

Annex D - Examples of RCUK-TSB Collaboration

Across the Research Councils over 90 new activities have been initiated in partnership with the TSB since 1 April 08. Highlights include:

Innovation and Knowledge Centres (IKCs) A partnership between EPSRC, BBSRC and TSB. Two new IKCs were launched early 2009 and a call for a further two will be opened in November 2009. Each centre receives £6.95m from the RCs and £2.5m from the TSB.	Centres of excellence to accelerate and promote business exploitation of emerging technologies. Combining the best research with best business development, market analysis and commercialisation skills
New interventions (feasibility and fast track awards) for the Creative Industries The RCs (especially AHRC) worked closely with TSB in shaping the plans in this area.	Smaller, shorter awards with a light touch application and assessment process to better suit the needs of the micro-enterprises and SMEs in the creative industries sector.
A new **KTN for the Financial Services** The call was developed in close collaboration with the RCs. TSB, ESRC and NERC investment in the KTN is expected to total almost £3m over three years.	The KTN will share knowledge and deliver innovation in the financial services sector, and will help businesses to innovate by providing them with networking and partnering opportunities and with up-to-date knowledge on markets and technologies.
Joint ESRC-TSB seminars in association with Innovation Platforms For example a seminar 'Social and Behavioural issues influencing the development and adoption of Assisted Living Technologies' in September 09 will inform the scope of a new call for research that will open November 09. The call we be jointly funded by TSB, ESRC and the Department for Health.	The seminars have provided value by: • Providing input towards the future strategy for Innovation Platforms; • Identifying new areas for RC-TSB funding programmes; • Introducing Innovation Platforms to a new set of stakeholders.
A new **NERC-TSB Design for Climate Change initiative** This activity was kick-started by a workshop between the construction industry and NERC research experts in December 08. The area will feature as a joint session at Innovate 09. NERC are providing funding for a critical review of the latest research evidence in climate change and this will be developed into an information pack for businesses. TSB will launch a Collaborative R&D competition in Spring 2010. The initiative will link closely with the Living with Environmental Change (LWEC) programme and the UK Climate Impacts Programme.	The aim of the initiative is to raise awareness of important climate change considerations within the construction industry to ensure that the UK has the knowledge and capability to build for the future.

Low Carbon Vehicles Integrated Delivery Programme (IDP) A five-year £200m programme funded jointly by Government (TSB, DfT, EPSRC, RDAs) and business. A £7m Strategic Programme led by EPSRC to develop a portfolio of university based research focussed on key longer term technologies for lower carbon vehicles is an important element of the IDP.	The IDP will co-ordinate the UK's low carbon vehicle activity from initial strategic research through collaborative research and development, leading to the production of demonstration vehicles.
Innovation Research Centre (IRC) The IRC and related distributed projects will be funded by ESRC, DIUS, NESTA and the Technology Strategy Board (£5m over 5 years).	The IRC will advance knowledge of a broad definition of innovation through high-quality, independent, research that is fully engaged with policy and practitioner communities. It will ensure the maximum impact of new knowledge on policy and practice and develop capacity, in terms of people, data and methods, for future research and knowledge exchange.
Carbon Crucible A partnership between NESTA, RC Energy Programme, UK Energy Research Centre and TSB. A new leadership programme for a select group of 30 early stage researchers in energy from business and academia.	Participants will gain new skills and contacts and develop transformative ideas with an opportunity to bid for funding to take forward proposals developed during the crucible programme.
Ensuring Privacy and Consent (EPAC) in Identity Management Infrastructures sandpit (EPAC) Funding partners: TSB; Identity and Passport Services (IPS); Home Office; EPSRC and ESRC.	The sandpit encouraged free-thinking, delved deep into the problems on the agenda and uncovered innovative solutions. As a result of the sandpit three new multidisciplinary academic-business consortia were supported with a value of £5.5m.
Knowledge Centre for Materials Chemistry (KCMC) Funding partners: NWDA, Universities of Bolton, Liverpool, Manchester, and STFC, managed by the Chemical Innovation KTN.	The KCMC is a virtual centre of expertise providing multi-disciplinary research and innovative knowledge transfer based on world class capabilities in applied materials chemistry. Total budget £15m (STFC £0.5m).
Regenerative Medicine A programme of investment in key areas of commercial R&D and the development of R&D partnerships. TSB funding will be £18m with the MRC, EPSRC and BBSRC providing additional funding of at least £3.5m.	The number of UK companies working in this field has been growing since 2003 and the UK is a world leader in this area, with a strong academic science base and a supportive clinical and regulatory environment. The programme will help the UK to fulfil its potential in this field by addressing a number of development challenges which need to be overcome to successfully commercialise promising discoveries.

In addition:

Collaborative R&D Competitions

1. All RCs have engaged with TSB-led competitions for Collaborative R&D. On average, the RCs provide approximately 15% co-funding towards competitions.

Knowledge Transfer Partnerships (KTPs)

2. The RCs continue to be key partners for KTPs and have been closely involved with the plans for doubling the number of KTP awards and increasing the flexibility of the KTP product. A variety of different KTP programmes have been developed in partnership, e.g.:

- ''Modelling Large Losses in the Insurance Industry'' – a KTP programme developed by the Insurance Intellectual Capital Initiative, TSB, NERC and ESRC.
- Shorter KTPs in association with IDEAs at Daresbury – projects between Business Schools involved with IDEAs and SMEs on the Daresbury Campus. A partnership between ESRC, TSB, STFC and the IDEAs collaboration.
- The Cubesat KTP challenge - projects to design experiments within Cubesats. An annual competition will be held to select a successful project and experiment to be launched into

space. A partnership between TSB, STFC, the Cubesat network and the Sensors and Instrumentation KTN.

Knowledge Transfer Networks (KTNs)

3. The research community accounts for approximately 25% of the total KTN membership (57,000) with the remaining 75% being largely private sector. The RCs continue to work closely with KTNs, for example:
   - KTNs acting as "agents" for EPSRC Industrial CASE awards.
   - KTN staff managing the BBSRC Research and Technology Clubs.
   - Special Interest Groups (SIGs) supported by the Research Councils, e.g. the Research Instrumentation SIG with the Sensors and Instrumentation KTN supported by STFC, BBSRC and NERC.
   - RCs commissioning KTNs to run specific activities: workshops, showcase events, roadmapping sessions.
   - RC co-funding for new KTNs, e.g. Financial Services KTN.
   - RCs are actively involved in the current process to optimise the KTN portfolio. For example RCs, represented by STFC, are actively involved in the oversight of the formation (by merger) of the new Electronics, Sensors and Photonics KTN.

Strategic engagement

4. There is good cross-representation from RCs/TSB on high level strategic groups, for example:
   - TSB representation on RC-managed advisory bodies includes – MRC Pharma Forum, LWEC Partners Board, STFC Knowledge Exchange and Economic Impact Advisory Group, BBSRC Bioscience for Industry Strategy Panel, Digital Economy Programme Advisory Board, RC Energy Programme Coordination Group, etc.
   - RC representation on TSB-managed advisory bodies includes – TSB Governing Board, Strategic Advisory Group with RDA/DA Science and Industry Council Chairs, Innovation Platform Steering Groups (inc. Assisted Living, Intelligent Transport Systems and Services, Low Carbon Vehicles, Network Security), KTP Management Board, KTN Steering Committees, etc.
   - A Strategic Partnerships group involving the heads of Innovation and KT from each RC, RCUK, BIS and senior staff from Technology Strategy Board meets quarterly to identify ways for the RCs and the Technology Strategy Board to accelerate innovation, to undertake horizon scanning to shape future programmes, to develop good working relationships, to ensure programmes are in place to deliver the financial targets and to learn from implementation of joint programmes.

Professor Richard Noss

Teaching and Learning Research Programme – **Technology Enhanced Learning**
London Knowledge Lab
Institute of Education, University of London
23-29 Emerald Street
London WC1N 3QS

28 August 2009

This short note is aimed primarily at contributing to point 7: What are the future challenges for STEM education at primary, secondary and tertiary levels? My starting point is that digital technologies, have a vital and potentially transformative role to play in the learning and teaching of STEM subjects – not to overstate the case, *we cannot rise to the challenge of learning and teaching STEM subjects without carefully-designed, thoughtful and well-researched use of digitial technologies.*

T is not high on the agenda compared with S, E and M. Mostly, it is thought of as a 'subject to be learned', rather than a means to an end. In fact, there is a vibrant research field in 'Technology Enhanced Learning' (TEL) - that aims to improve the quality of learning in STEM and other subjects, and to make accessible forms of knowledge that were simply inaccessible before. In other words, there is scientific knowledge that is simply too hard to teach with pencil, paper and books – too hard for most people most of the time. Now, with digital technologies, some aspects mathematics and science, for example, can become teachable (and engaging) in ways that were simply unthinkable in the pre-digital age. Two examples: *Dynamic geometry* – in which Euclidean (and non-Euclidean) relationships are preserved under continuous 'dragging' (http://en.wikipedia.org/wiki/List_of_interactive_geometry_software); NetLogo, a multi-agent *programmable modeling environment* that allows even quite young learners to build mathematical models of scientific and social-scientific systems (http://ccl.northwestern.edu/netlogo/). These two examples illustrate what is possible, and they rest on a *huge* input of research that brought them to fruition.

But research does not translate easily into practice, at school, in higher education or in the workplace. The forms of pedagogy that characterise learning in these settings have remained more or less invariant even when radical technologies have been introduced. And genuinely transformative technologies such as those described involve a substantial investment of time and energy – and scientific/mathematical knowledge – on the part of the teacher.

STEM education has yet to come to terms with the importance of supporting individuals in developing the capability to produce their own knowledge, rather than merely consume the knowledge of others. There is a nascent attempt to develop learners' skills of enquiry, analysis, synthesis, knowledge construction and collaboration: of course, the student's 'own' knowledge is worthless if it doesn't align with scientific knowledge! The teaching of T has a crucial role in and of itself. But much more research and teacher development is needed to find ways to enhance the teaching of S, E and M using T.

The Teaching and Learning Research Programme: Technology Enhanced Learning programme is funded jointly by the ESRC and EPSRC. It currently comprises eight large-scale interdisciplinary research projects, and an emerging range of thematic commentaries and research briefings based on their findings. See www.tlrp.org/tel for details.

Professor Richard Noss
Director: TLRP-Technology Enhanced Learning.

Professor Andrew J. Oswald

As requested, here are two articles that I hope might be useful to your inquiry.

"The Elite Brain Drain" shows how mobile top scientists are, and that they migrate towards the high R&D nations. It was published in The Economic Journal this year.

"A Suggested Method..." is a way of calculating how good a nation is at (really) major scientific achievement. It will appear next year in Scientometrics. It shows that UK economics does well, consistent with the RAE results. But it would be good if my calculations could be checked for a wide range of UK subjects.

Best regards, Andrew

The two papers are:

A Suggested Method for the Measurement of World-Leading Research (Illustrated with Data on Economics)
Andrew J. Oswald
University of Warwick and IZA
Discussion Paper No. 4313
July 2009

THE ELITE BRAIN DRAIN[53]
Rosalind S. Hunter, Andrew J. Oswald and Bruce G. Charlton

[53] For many helpful suggestions, we thank three referees and Robin Ball, Sandra Chapman, Joseph Falkinger, Amanda Goodall, Simon Hands, Steve Machin, Robert May, Robert MacKay, David Spiegelhalter, Richard Tol, Radu Vranceanu, Fabian Waldinger and co-authors on the unpublished paper by Warwick University (2007), especially Showkat Ali and Hilda Ralsmark, for allowing us to draw upon some of the results described there. We are extremely grateful to all the physicists who replied to our emails. Oswald's work was supported by an ESRC research professorship.

Professor Robert Paton
The Royal Society

The Fruits of Curiosity: Call for Evidence

What follows is a brief summary of my personal thoughts and opinions, rather than those of my employers, informed and influenced by research and engagement with practice, relating in the main to the implementation of cross disciplinary STEM initiatives. In particular, I draw down upon my recent experience in the emerging fields of services science and innovation, within a management/systems context.

As noted by the recently published Royal Society *Hidden Wealth* report, Science and Engineering have clearly had a role to play in underpinning the services revolution; they have both driven and enabled countless ICT and business innovations. My main concern is that although one cannot deny the role and importance of STEM, we appear to be lagging behind our major competitors (USA/Europe). A cursory internet search on 'services science' will show where the interest, innovation and leadership lies. We will quickly fall by the wayside, as our competitors more open and progressive view of the world of research and teaching continues to deliver sustainable curiosity driven multi-disciplinary research and suitably prepared graduates.

We are mainly organised in disciplinary silos, which in turn are assessed and rewarded by measures relating to core subject relevance and visibility. We 'talk a good game' when it comes to multidisciplinary activity, but not enough of the players on the ground actually belief it to be so. This in turn impacts upon the majority of both STEM and Business graduates that we produce. The non-core disciplines tend to be delivered by 'service' departments in silos. Multi disciplinary impacts can be minimal.

When one looks at the emerging disciplines, for example, practitioner stimulated and driven services science and innovation, one finds that the UK is lagging behind the US, Scandinavia and Germanic states, in terms of both hard research and teaching initiatives. We tend to seek the 'funds' and *talk* rather than engage with practice and develop fundable opportunities. Taiwan, India and even China seem to have grasped the basic idea that services contribute more than product, and innovation in this sector must be multidisciplinary.

We have to match the KPI's to the rewards and be seen to be doing so in a general rather than ad hoc manner. Research funding, tuition fees and teaching grants must be aligned with the needs of a STEM driven service economy. We must also embrace industry and commerce on a partnership rather than what's in it for us basis. Risks and rewards must be more openly shared with industrial partners and curiosity related research better integrated with knowledge transfer initiatives.

Working across boundaries, embracing practice, satisfying QA and research agendas, all take time. At present I fear that most academic staff understand the need to embrace change and face the multidisciplinary challenge, but can see no real benefit in abandoning the known parameters of success.

Professor Robert Paton
Director of the Complex Service Innovation Network
Department of Management
University of Glasgow