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THE ROYAL SOCIETY

The Scientific Century: securing our future prosperity

(Final report of the Fruits of Curiosity inquiry)

Responses to Call for Evidence
Part II

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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

Professor Harold Thimbleby

Fruits of Curiosity: science innovation and future sources of wealth

The Royal Society's Call for Evidence for the role science will play in equipping Britain in the next twenty years mentions STEM subjects, but it does not mention the science that has changed every aspect of our lives: Computer Science.

Computer Science supports everything we do, but it remains hidden, trivialised, and in consequence its broad and fundamental role in future wealth generation, social benefits, is often overlooked.

Take a very simple example. Almost every use of computers involves sorting, putting things into order. This was only recently a cutting-edge research problem, and it is still a serious area of advanced research. But to most people, you just pull down a menu in Excel and sort a table, or you just click on something on the screen and you don't even realise the coordinates of the mouse are looked up in a sorted table. The science has become hidden because it works so well. To ignore Computer Science is a bit like thinking we don't need to do research in transport, engines, energy, and so on, because you can buy cars ready made. I remember Roger Needham FRS saying that there is an undercurrent in Britain that we do not need to do Computer Science because if we can buy it from Microsoft, why do the research in the UK? We have an entrenched view that Computer Science is stuff you buy and learn to use, not stuff you can think about, innovate in and create wealth with. The intellectual content, and with it the potential for new invention and wealth creation (and social benefit) is ignored. Computer Science doesn't seem to the vast majority of people to be difficult or worthy of research, because what works and took serious science to create requires no understanding to use.

We need a clearer idea of the very distinctive nature and contribution of Computer Science. In particular, to think about the future sources of wealth for Britain, we need to think of today's children and the educational system that locks them in to particular world views for the rest of their lives — and, in turn, locks-in the teachers of the next generation. Most people do not realise there are different sorts of science, and hence different ways to reify each to gain economic and societal gains.

Almost all sciences are *natural sciences*, in Herb Simon's terms. For example, medicine seeks to understand phenomena in the natural world (specifically human health) and there is a wellrehearsed process (including regulatory approval) for translating specific problems and understandings into dependable products for markets, such as pharmaceuticals. Because the unknowns and problems (let's say: cancer) are pre-existing, the markets are well-defined and the funding is predictable. Biology, physics, maths, chemistry are much the same in form, except often there is a more tenuous link between research and future sources of wealth and social well-being. In artificial sciences, for example, computer science, we are creating solutions and insights to problems that did not previously exist, and for which there is little consensus of viable research directions. (Of course Computer Science also solves known problems, such as ABS in cars, or GPS algorithms.) Ideas like digital cryptography create new concepts such as digital rights management (DRM) that create income streams and opportunities for trade that were inconceivable a year before.

The Royal Society wishes to challenge the separation of "pure" and "applied" research. Computer Science has a third way: programs are fundamental objects of research but do not make this distinction. There is no real sense of doing pure research with, say, bench test tubes that is clearly different from doing applied industrial production. I have a PhD student who developed a nice piece of mathematics (pure?) and within months he had sold over 250,000 copies of it (applied?) but in this there was no intrinsic distinction between pure and applied. It was a program.

In fact this new concept is one of Computer Science's problems: there are too many people innovating and developing real applied systems, but where the science and engineering underneath it is hopeless because they can't see that there is a difference between making something work at home in a demo and making it work in unpredictable contexts of use. That's why programs crash. As a society — even the society of our top scientists — we are largely unaware of how hard real Computer Science is. We gloss the exciting challenges of Computer Science, and let lucky but incompetent "scientists" make profits.

Another tradition Computer Science blurs is the "lone inventor" model. We like to imagine Thomas Edison sweating away inventing things and then producing wealth. In Computer Science I can't make a "light bulb" (not that Edison did anyway, but that's another story) because anything I do relies profoundly on close integration with hundreds of other innovations that are hedged around with IPR. An idea for a program relies on a compiler, APIs, hardware, connectivity, sensors, memory and so on. Without the infrastructure it is worthless. Unfortunately this means that the energy in working on "applied" Computer Science ideas is almost entirely directed to business and legal work, thus reinforcing the mistaken impression that the science that makes it work dependably is insignificant, or merely technical.

Although Computer Science now underpins all other sciences and all areas of finance and business, and has created and made possible new sciences (e.g., genomics, computational chemistry, (modern) particle physics, climate monitoring…), and has even transformed refereeing and all office procedures, we still don't have a clear story of how investment in Computer Science research leads to economic or social benefit. We definitely don't have a clear idea about how to teach Computer Science or to build on children's enthusiasm for computers. Instead schools stifle interest in Computer Science, substituting a consumerist skill base. My main message to the Royal Society is that if we do not sort out teaching and enthusing children about computer *science*, we will have nothing both British and competitive in twenty years' time. Take Amazon or Google as simple success stories. They both solve problems none of us realised we had until they solved them (of course, there were a few proto-solutions to both, but only afficionados realised these were problems worth solving: and then, almost overnight, the whole world sees that Amazon is just what they need). SMS, Facebook, the web itself, ... none of them were solutions to problems anybody (apart from a few visionaries) had defined *a priori*. Hardly anybody worked on them. There was no "race" to discover the web, like there are races over the Higgs Boson, the human genome, or Fermat's Last Theorem. Without computer science, who would have used network analysis to seek out terrorists? The core of Computer Science is very unlike medicine, engineering, physics, or maths, then. Unfortunately, now that Computer Science is supporting Amazon and Google, the focus turns to them as business case studies, not as drivers of excitement in Computer *Science*.

Or take keys. Locks and keys have been around for at least 4,000 years, and we take them for granted and expect them on every door. Thanks to digital cryptography, hotels can now give us keys (e.g., RFID cards) that work perfectly like keys always have done, except you can take them home, and if you went back to the hotel after you'd left — even if you didn't check out — you'd find the key did not unlock the door. You might have thought nothing has changed, but some serious Computer Science innovation behind the scenes has changed the rules. Few people understand this, even fewer are able to teach the principles behind it. We end up with another generation of children who are consumers rather than creators of new technology, unable to see new solutions to old problems, or new innovations to new problems. We end up with leaders in business outsourcing out of the UK rather than investing.

Computer Science is valuable to the UK because it is visionary. It will provide solutions to problems we don't know we even have, in addition to doing all the good things underpinning everything else (making them faster, more reliable, smaller, lower power, easier to use, *etc*). By providing solutions to unknown problems, by definition, Britain would stay competitive because other countries would be catching up and being consumers of *our* innovations.

Of course, Computer Science is also improving solutions to known problems and making us more competitive in more well-defined ways, just like other sciences do, but it is also giving us a skill base and an intellectual base to transform the world in a way few other sciences can dream of (perhaps nanotechnology excepted).

In my view, Computer Science is dreaming dreams that other sciences don't have and actually don't have — or need — the imagination to have. Computer Science translates unknown unknowns into tools that anybody can exploit — and they still won't have a clue how the algorithms underneath work. Computer Science is driven by dreams of the future, whereas almost every other science is driven by refining the problems we already know about. (Obviously, any science can have the occasional paradigm shift with a new concept, but this is unusual and not their normal mode of operation.)

As a field, Computer Science has only been around a few years, yet it has to convince society it is, in crucial ways, more valuable than disciplines such as astronomy and biology that have been heavily funded for really no better reasons than for centuries we have been sentimental about stars and bunnies. We may be finding our place in the universe and natural order of things thanks to them, but humans still don't know how to think, whether about current problems or about future ones. Improvements to how we think and think about thinking and how and what is delegated to computers (or what computers

delegate to us) are going to the only hope for mankind's future, let alone the Britain's. Innovations like wikis, email, twitter, *etc*, *etc*, change how we work and relate. Many more will come in the right environment.

I fear that the UK is no longer the place to expect innovation in Computer Science. The UK has already seen the brief rise and demise of many computer companies. We were once leaders, but our venture capitalists, tax structures and much of our social environment failed to understand how to support innovation. Those stifling cultural factors arose out of adults who had once been children badly taught about science and innovation.

There might be a temptation to dismiss my thoughts as a rant … I have certainly painted contrasts that may seem to overstate my case at the expense of colleagues in other disciplines. But consider: Computer Science is unstable and rapidly changing. The core technologies I use in my own research today are different from what they were last year, and that happened last year too, and the year before. What other science is developing so fast and so unpredictably? I've had papers rejected because referees did not understand them, and then rejected six months later because there then a commercial product doing much the same thing, so what I am doing is no longer research.

Now is the time to harness the excitement that Computer Science is really all about, rather than what consumerism is all about: *that* will drive the future for Britain, particularly when we stimulate the curiosity of children. Today's children will become not just tomorrow's innovators, but they will become journalists defining out culture, teachers nurturing the next generation, and so on. Some might become future "web designers" — a career that didn't exist before 1994 — or having a career that doesn't exist today.

I'd get a bunch of early career researchers, distinguished professors plus a few teachers and students together for a science/art week (or series of workshops) to devise a sustainable structure (which *might* mean defining syllabus and qualifications) that would work in UK schools and stimulate the next generation with the excitement, skills, curiosity, confidence and hope to drive future sources of wealth and wellbeing. (There's a lot I haven't space to explain or justify … like making sure we get a healthy gender balance, *etc*.)

Prof Harold Thimbleby
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Institute of Engineering and Technology

Transforming Engineering Education
A report on the first year of the new Engineering Diploma for 14-19 year olds

1. Executive Summary

Diplomas are new qualifications for 14 – 19 year olds, to be studied alongside other qualifications such as GCSEs and A-Levels. The Engineering Diploma was one of the first five Diplomas to be introduced from September 2008.

The Engineering Diploma was developed with significant input from employers and the curriculum ensures that students develop engineering skills, literacy and numeracy, and 'employability skills' such as team work.

The Diploma allows students to experience 'real life' engineering and to work on projects similar to those faced by engineers working in industry. The new qualification is taught by schools and colleges working in partnership with employers. Diplomas can be completed at different levels, and can serve as preparation for employment, apprenticeship or university.

Over the past year, almost three thousand students have taken up the new qualification. The number of students studying the Engineering Diploma is expected to increase significantly in coming years. From 2013, all pupils will have an 'entitlement', whereby, if they have achieved the required standard and want to study for the Engineering Diploma, they will be guaranteed a place on the course.

The IET is pleased with the way the Engineering Diploma is being implemented, and that concerns we have expressed in the past have been addressed. In particular, the IET welcomes the fact that the new qualification is providing a challenge even for very able students. Engineering Departments at universities are recognising that the Diploma can be a first step towards acquiring high level skills. An analysis of the entry requirements for engineering courses at Russell Group universities, carried out in May 2009, found that the Advanced Diploma is accepted for admission to 79% of available courses, provided students achieve sufficiently high grades and have studied certain options. The Engineering Diploma has been expressly welcomed by many of the top universities in the country, including Oxford and Cambridge.

For the IET, and the engineering community more broadly, the Engineering Diploma now offers a unique opportunity. In the past, if taught in schools at all, engineering has tended to be an extra-curricular activity. The result is that students have developed little or no knowledge about engineering and engineering careers. The Engineering Diploma has the potential to change this, by placing engineering at the heart of the school curriculum for the first time.

There are nevertheless challenges still to overcome. The public profile of the new qualification must be improved. Schools and colleges must ensure the various components of the course are delivered in a coordinated manner. The proportion of female students studying for the Engineering Diploma must increase, because the current proportion of 7% will not improve the gender balance of the engineering sector. Careers education and guidance must improve in quality and quantity, in line with the increased learning options available to students. Crucially, high standards must be maintained as availability of the Engineering Diploma expands. By meeting these challenges, we will ensure that this new qualification has a very positive impact on engineering in the U.K.

2. Context

The introduction of the new Diploma qualifications for 14 to 19 year olds followed publication of the White Paper *14-19 Education and Skills* in February 2005.

The Engineering Diploma was amongst the first wave of Diplomas introduced from September 2008 alongside Diplomas in Construction and the Built Environment; Creative and Media; Information Technology; and Society, Health and Development.

Additional Diplomas are being introduced year on year, so that by 2011 there will be seventeen to choose from.

The composition of the Engineering Diploma

The Engineering Diploma develops students' understanding of engineering principles and how to apply these principles to real life situations. As with all the Diplomas, at least 50% of learning must be applied. The curriculum for the new qualification has been compiled with significant input from employers. The Engineering Diploma develops students' engineering skills, literacy and numeracy, and 'employability skills' such as team work and the ability to manage an extended project.

Levels of the Diploma
The Engineering Diploma is taught at three levels:
Foundation (Level 1 – equivalent to 5 GCSEs at grades D - G).
Higher (Level 2 – equivalent to 7 GCSEs at grades A* - C)
Advanced (Level 3 – equivalent to 3½ A-levels)
Typically, students study for the Foundation or Higher Diploma in Years 10 and 11, alongside GCSEs in the compulsory national curriculum subjects. They study for the Advanced Diploma in Years 12 and 13. In some instances, the Foundation and Higher Diplomas are being run as a one year course for post-16s. Whilst students who have not previously studied for the Higher Diploma can study for the Advanced Diploma, it is anticipated that many students will complete the Higher Diploma and then progress on to the Advanced Diploma.
The Diploma has been designed to prepare students for either employment, an apprenticeship, or university.

The partnership approach
The Engineering Diploma is delivered by consortia of schools, colleges, employers, universities and other stakeholders. The partnership approach allows for pooling of resources meaning that, for example, a student whose main base is a school can also make use of engineering equipment at the local college. Employers and universities also contribute, for example by inviting groups of students to visit their sites, sometimes to receive lessons, and by setting engineering tasks for completion at school or college. Employers are expected to aid curriculum planning and assessment.
The size of consortia differs from place to place, from very large consortia covering whole cities to small consortia comprised of just a few schools and a college.
Students typically divide their time between educational institutions. For example, a Higher Diploma student in Year 10 or 11 may spend four days a week at school and one day a week at their local college. Consortia arrange for students to travel from place to place, usually by minibus.

The curriculum
At each level, the Diploma consists of:
Principal Learning. This covers broad engineering skills. The specified elements include:
- 'The Engineered World: the importance and impact of engineering on our lives'.
- 'Discovering Engineering Technology: basic engineering principles'.
- 'Engineering the Future: what makes innovations succeed, how new materials contribute to design, how to develop and .launch new ideas'
- 'Analytical methods for engineering' (Advanced Diploma only).

Generic Learning. This part of the course will in some instances be given separate space in the timetable, but will often be embedded within the compulsory aspects of the national curriculum. Generic Learning includes:
- Functional skills - equipping learners with the necessary knowledge and understanding to use and apply English, .Mathematics and ICT in everyday life.
- Projects – students are required to complete an extended project..
- Personal, Learning and Thinking Skills (PLTS) – this element of the course aims to develop the ability of students to operate .as independent enquirers, creative thinkers, reflective learners, team workers, self-managers and effective participators.
- Work experience – all Diploma students will be required to complete a minimum of ten days work experience. .

Additional or Specialist Learning (ASL). For ASL students may study:
- Additional Learning - qualifications from outside engineering, for example, a Higher Diploma student might study for a .GCSE in Business Studies as part of their ASL, whilst an Advanced Diploma student might study for an A-level in Business Studies.
- Specialist Learning - engineering qualifications which deepen students' knowledge of engineering, for example, EDEXCEL .has developed a new aerospace engineering qualification that Advanced Diploma students will be able to study as Specialist Learning.

Example of a student's timetable
Here is an example of the timetable for a Year 10 Higher Diploma student in Bristol. This demonstrates how the Diploma fits into the broader curriculum.

	Mon	Tues	Wed	Thurs	Fri
Lesson 1	Diploma Project	Functional IT	Engineering	French	English
Lesson 2	Religious Studies	Science	Engineering	PE	Science
Lesson 3	Science	PE	Engineering	Citizenship	Mathematics
Lesson 4	English	English	Engineering	Diploma Project	French
Lesson 5	Tutor Time	Tutor Time	Engineering	Tutor Time	-
Lesson 6	Mathematics	Mathematics	Engineering	Business Studies	Science
Lesson 7	-	-	-	Business Studies	-
Location	School	School	College	School	School

Key:
Principal Learning
Additional or Specialist Learning (ASL)
Diploma Project
Functional Skills in English, IT and Mathematics embedded in these courses
Notes:

- Personal, Learning and Thinking Skills (PLTS) embedded across the curriculum and recorded by the student.
- Science, Mathematics and English are all obligatory for Year 10 students as 'core' national curriculum subjects, and this student is studying towards GCSEs in these subjects. PE and Religious Studies are statutory requirements.
- The student is studying towards a GCSE in Business Studies as their ASL.

3. Availability and uptake of the Diploma

Availability across England

Sixty two consortia offered the Engineering Diploma in the academic year starting September 2008, with a further eighty three consortia set to offer the Diploma from September 2009.
Consortia need to apply and be accepted to offer the Engineering Diploma, by means of the 'Gateway Process'. The Gateway Process for consortia hoping to offer the Engineering Diploma from September 2010 is not yet complete, but more than twenty five consortia are expected to complete the process and start offering the Engineering Diploma from 2010.
There is currently some unevenness in availability across England. In 2009/10, there will be twenty four consortia offering the Diploma in the North West but only six in London, as demonstrated by the table below.
The number of consortia passing through the Gateway must increase in coming years in time for the introduction of the 'entitlement'. From 2013, all pupils will have an entitlement whereby, if they have achieved the required standards and want to study for the Engineering Diploma, they will be guaranteed a place.

Region	Number of consortia offering the Engineering Diploma 2008/09	Number of consortia offering the Engineering Diploma 2009/10
North East	6	13
Yorkshire and Humberside	3	14
North West	12	24
East Midlands	11	20
West Midlands	10	23

East England	3	10
London	4	6
South East	11	22
South West	3	14

Uptake amongst students
2,780 pupils started studying for the Engineering Diploma in September 2008, and in March 2009 2,542 students were still on the course. The number of Engineering Diploma students is expected to rise significantly over the next two years. In September 2008, 23% of all Diploma students were studying Engineering, and the proportion had risen to 25% by March 2009.
Of the pupils studying for the Engineering Diploma during its first year:

- 15% were studying at Foundation Level.
- 64% were studying at Higher Level.
- 21% were studying at Advanced Level.

The proportion of students studying for the Advanced Engineering Diploma is expected to increase in coming years. At present a high proportion of consortia are not offering the Diploma at the Advanced Level, but it is anticipated that many of these consortia will start to do so from September 2010, so that their students who started studying for the Higher Diploma in September 2008 can progress onto the Advanced Diploma upon completing the Higher.
16% of students taking the Engineering Diploma are eligible for free school meals, roughly the same proportion of pupils eligible for free school meals across the whole school population.

4. What are the merits of the Engineering Diploma?

Skills shortages in engineering
There are substantial skill shortages in engineering. Research carried out by the IET this year found:

- 36% of companies report skills shortages amongst new engineering recruits, with 21% reporting a lack of technical skills..
- 53% of companies report skills shortages amongst newly recruited school leavers.

These skills shortages indicate the need to revitalise education in engineering. As laid out below, the Engineering Diploma is an opportunity to achieve this. The IET is pleased with the way the Engineering Diploma is being implemented and that concerns we have expressed in the past have been addressed.

How the Diploma will address skills shortages
Developing the right kind of skills
The Engineering Diploma has been developed by employers to ensure that students develop the skills required by industry. Employers require technical engineering skills, literacy and numeracy and 'employability' skills such as teamwork.
The Diploma is a challenging option. Universities recognise that students who have completed the Advanced Diploma and achieve high grades will make strong candidates for places on undergraduate engineering courses.
The Russell Group is an association of twenty major research-intensive universities, and includes most of the leading universities in the country. An analysis of the entry requirements for engineering courses at Russell Group universities, carried out in May 2009, found that the Advanced Diploma is accepted for admission to 79% of available courses, provided students achieve sufficiently high grades[1]. Only 13% of engineering course requirements expressly stated that the Diploma was deemed unsuitable for entry, and this proportion is likely to drop in coming years as knowledge of the new qualification increases.
Universities that support the Diploma include Oxford and Cambridge, which have both issued statements supporting the Engineering Diploma.
Many universities do stipulate that Diploma students should use their ASL to study certain courses (typically universities ask for Maths A-Level or the new Maths for Engineering course as the ASL).
Sometimes the requirement for Maths qualifications has been misinterpreted in the media because of a lack of understanding about the structure of the Diploma. Commentators have suggested that universities are demanding that students complete Maths A-level *in addition* to the Diploma, with the inference that universities do not have faith in the new qualification. In reality, universities are asking that students complete Maths A-level *as part of* the Diploma, through the ASL component.

[1] Analysis carried out on behalf of the Engineering Diploma Development Partnership (EDDP) Strategy Group
[2] Study carried out by The Trading Edge Co on behalf of the IET

[3] Implementation of the 14-19 reforms, including the introduction of Diplomas (Ofsted, August 2009)

Putting engineering at the heart of the school curriculum
In September 2008, before the Engineering Diploma had time to make any impact, the IET commissioned a comprehensive study of attitudes to engineering amongst school students. The study was based on a questionnaire completed by 606 pupils from twelve secondary schools across the country, followed by six in-depth focus group discussions with 69 mixed-ability pupils from Year 9 and Year 10 across a selection of these schools[2].
This study found that students' knowledge and understanding of engineering was poor. 91% of pupils said they knew little or nothing about jobs and careers in engineering. Many assumed that engineering was necessarily manual and dirty, with 33% of students associating engineering with a 'dirty working environment'.
When asked to spontaneously suggest three words associated with engineering, pupils tended to focus more on the implementation ("fixing things") rather than the creative, problem solving or design side of a professional engineer's role.
However, this did vary from school to school and a few pupils who were more aware of engineering, due to a motivated teacher or extracurricular activities, had a more positive view. They associated engineering with words such as: "clever", "pays quite well" and "an engineer designs things and brings them to life".
More students should have the opportunity to develop a positive understanding of engineering. Rather than relying on individual teachers with a passion for engineering, or availability of extra-curricular activities, engineering should be placed at the heart of the curriculum. The introduction of the Engineering Diploma is a rare opportunity to do just that.

Making engineering interesting
The study of attitudes to engineering amongst school students asked participants what they thought made lessons in science, technology and engineering interesting. The two factors most associated with interesting lessons were good teachers and strong practical content.
Students made comments such as:

- "I hate it when we just have to copy from the board".
- "The best lessons are those where there is some relevance to us as teenagers - how things apply to the world"

Given these attitudes, the applied nature of the Engineering Diploma means it is much more likely to engage students than other qualifications. Practical and applied elements built into the Diploma include:

- Explanation of the relevance and importance of engineering to everyday life
- Links between theory and practice
- Tasks set by employers, based on real-life engineering problems
- Day visits to work places to see engineering in action
- Work experience

An extended project, including strong practical elements

Experiences and attitudes to the Diploma after its first year

The student experience
Vicki and Sorcha, Higher Diploma students in Orpington
Vicki and Sorcha are just starting Year 11 at Newstead Wood School for Girls in Orpington, a high achieving grammar school which specialises in engineering and languages. They have completed the first year of the Higher Level Engineering Diploma.
Vicki says: "I am very interested in engineering, and when I was in Year 9 making my choices I decided to go for the Diploma because of the range of areas of engineering it covers. As we're a specialist engineering school, I could also have done the GCSE in Systems and Control, but the Engineering Diploma covered this and much more as well."
She added: "With the Engineering Diploma, you get to travel to Bromley College and use their equipment, which is excellent."

[2] Study carried out by The Trading Edge Co on behalf of the IET

Sorcha agreed: "As someone interested in engineering, the Diploma seemed the most interesting option. I liked that it had strong practical elements, including technical drawing and the use of a wide range of tools and machinery."
She goes on: "I definitely made the right choice, as I have really enjoyed the Diploma. It's different to what we get in Design & Technology". Vicky added: "With the Diploma, you get to look at all aspects of products like a manufacturer in the real world."
One of the areas of focus in their first year of study for the Diploma was mechanical engineering, which they learnt about at the college. The students have been involved in the manufacture of a hydraulic lift system, which they tested and evaluated against the relevant scientific principles. They have also mass produced motor stator laminations, facilitated by a jig, fixture and punching tool which they developed. These tasks enhanced the students' skills in teamwork, planning and problem solving as well as expanding their engineering knowledge and understanding.
Over the coming year, the focus will move to systems engineering, with the students designing control systems and building their understanding of electronic circuitry and components.
Both Vicki and Sorcha have begun to think about what they might like to do in the future. Newstead Wood School offers the Advanced Diploma, and both girls think they might take this option. Sorcha says: "Obviously I will have to see, but I do like the idea of doing engineering for a career, maybe civil engineering or aerospace. One of the good things about the Diploma is that I know it is designed by employers and covers what they think is important."

Adam Young, Advanced Diploma student in Stevenage
Adam, an eighteen year old from Stevenage, is studying for the Advanced Engineering Diploma.
Adam explains: "I completed my GCSEs and started to study for four AS Levels at my school, but I did not really get on in the sixth form. I felt they concentrated on the younger children, not on us."
At the end of the year, Adam managed to complete two of his AS Levels, in Maths and Chemistry, but decided not to carry on at school for another year.
"I was looking round at what to do," Adam explains. "I liked the idea of engineering, and thought maybe I should do an apprenticeship. But then I saw an advertisement in the local paper for an Open Day at North Hertfordshire College, which I went to and heard about the Engineering Diploma. This sounded like a good option for me."
Adam started studying in September 2008, and has now completed the first year of the course. "I'm enjoying it," he says, "and the team teaching the Diploma here in Stevenage is excellent. I'm getting some real insight into engineering. We took a while to get started, but now we're really working through the units. So far we've completed modules that give you important background, in Maths and Physics, and a few modules looking at particular areas of engineering like metallurgy.
Adam explains the aspects of the course that interest him. "I like it when we see how the Maths and Physics relate to the real world. So we looked at what happens if you put, say, a force of 500 newtons on a specific material, calculating the Young's modulus. Young's modulus is a measure of the stiffness of an elastic material."
"We have also learnt about the safety procedures that must be carried out in the engineering environment. Some examples of this are when we carried out risk assessments and also learnt about all the safety regulations such as the 1974 Health and Safety at Work Act. We have completed a Business in the Engineering Environment module, which rolls in with the safety to create one single unit. It also covers different sectors of engineering, which helps us because it shows us all the potential sectors of engineering we could move into after we have completed the Diploma."
Over the coming year Adam will also study modules in Computer Aided Design, Instrumentation and Control, and Innovative Design and Enterprise. For the Advanced or Specialist Learning (ASL) component of the Diploma, Adam is studying for a Maths A-Level. "I want to go to university and study Motorsport Technology. I'm particularly interested in car aerodynamics, and would like one day to work in Formula One as an aerodynamicist."

The teacher experience
Frankley City Learning Centre, Birmingham
Frankley City Learning Centre Diploma Consortium consists of the Centre itself, where most of the teaching of the Diploma takes place, and five schools. The Centre has developed creative approaches to teaching the Engineering Diploma and gained a strong reputation for engaging employers.
Manager of the Centre Val Allen explains: "Right from the time we first heard about the new qualification, we wanted to teach the Higher Diploma. Frankley City Learning Centre specialises in Computer Aided Design and Computer Aided Manufacturing, so we already had great resources."

Students had to apply if they wanted a place on the Higher Diploma course. Val comments: "Many students were interested and, with competition for places, schools agreed to send us some of their best pupils. It's testament to the faith the schools have in us – and in the Diploma."
Students arrived at the Centre in September 2008, travelling by minibus to the Learning Centre for three days a fortnight. Since then, the teaching team has worked hard to make sure that the students have had as positive an experience as possible. The team has ensured a large amount of integrated theoretical and practical work, and put a major emphasis on Personal, Learning and Thinking Skills (PLTS). In addition, as Val explains, they have "sought to introduce students to as wide a range of engineering sectors as possible."
The Centre already had a group of partner employers who became the core Steering Group for the Diploma. Over the last 18 months the Steering Group has grown, and now consists of a dedicated and committed team. "We have an excellent supportive and committed Steering Group of employers," Val says, "including large national companies such as Cadbury, Landrover and the RAF and more local employers such as SRE and Hexagon Metrology, as well as organisations such as STEMNET. Aston and Coventry Universities provided engineering undergraduates to act as mentors to students at the Centre. Plans for introducing the Advanced Diploma here include the possibility of a Partnership with Aston University."
Employers have already worked closely with the students and teachers, acting as expert mentors for both groups. Greg Hill from the company Sustainable Renewable Energies, who erected the Centre's own Wind Turbine, ran workshops and practical sessions to prepare the students for their Unit One exam. The Centre held a launch day, in which TV presenter Dick Strawbridge "turned on" the Turbine and a representative from IMechE gave Diploma students IMechE Associate membership packs.
Cadbury have also worked closely with the students, offering a factory tour and presenting students with 'real life' engineering problems that actually exist on the factory floor. The students have worked on a variety of problems, with potential solutions presented to Cadbury's maintenance engineers.
The Centre adheres to the ethos of the Diploma. As Val explains: "The Diplomas are about developing students' readiness for the world of work. This means fostering self-responsibility, which we've done. Teachers back at the students' schools have remarked that the Diploma has changed students' attitude to work, giving them new found confidence and enthusiasm." Students appreciate the range of engineering specialisms they experience and relish the levels of responsibility expected from them. They feel that they are being treated as adults and respond accordingly.
"Our pilot has attracted interest from a range of people and has been reviewed by the Department for Children, Schools and Families (DCSF), a Prime Minister's Delivery Unit, and the Local Authority. All consider our delivery to be a very good model. The whole teaching team here feel great optimism for the future of the Engineering Diploma and are now looking forward to welcoming a new cohort of students and planning for the Advanced Diploma.

Sunderland Futures
Sunderland Futures is a consortium of the seventeen secondary schools in Sunderland, together with the local college and a network of work-based learning providers. The consortium stands out for many reasons, but most of all for its highly effective, city-wide approach.
When Diplomas were first announced, Sunderland was already planning two new centres for applied learning. The Harraton and Pallion Centres opened in September 2007 and since September 2008 have been offering many of the new Diplomas, including the Higher Diploma in Engineering.
Since September 2008, students have been travelling from across Sunderland to study for the new engineering qualification. There are 60 engineering students, who come for two half days per week, spending the rest of their week at their home school. Paul Graham, who is Head of Engineering and teaches the Diploma, says: "This is a difficult course, so we are only taking high achieving students. For students in Year 10 to analyse processes, really quite deeply, is remarkable. But with the Diploma they're doing so. It's a big step up from anything they will have done in Year 9."
Paul goes on: "Sunderland has benefited greatly because our education institutions have been prepared to work together. Not only does this mean that students do not miss out on the opportunity to study engineering, but economies of scale mean we are able to offer students great facilities. The centres are not like your typical Design and Technology classroom in a school – we have the equipment that you would see in industry, such as Computer Numerical Control lathes and mills alongside traditional manual machines, welding facilities and Computer Aided Design systems."
Sunderland has been able to bring together a team of teachers with different backgrounds, experiences and skills to ensure that students gain a thorough understanding of engineering. Paul himself worked in industry and has nineteen years experience in the automotive manufacturing sector.

The consortium has worked directly with a range of employers, including Caterpillar Peterlee, Rolls Royce, Black & Decker and Seaward Electronics. On a recent visit to Seaward Electronics, a group of Diploma students were able to learn how circuit boards are designed, tested and manufactured. As part of the unit Investigating Engineering Design, students have been disassembling a range of power tools donated by Black & Decker.
Paul says: "The Diploma in Engineering is revitalising engineering education and will provide students with the skills to go on to employment, apprenticeships or – at the Advanced level - university."

The university view
The University of York
The Department of Electronics at the University of York welcomes the introduction of the Engineering Diploma.
Dr Stuart Porter, Undergraduate Admissions Tutor, comments: "There's much to like about the Advanced Diploma. This new qualification covers many aspects of engineering, and will provide prospective university students with real understanding of what engineering is about."
Certain aspects of the Diploma particularly stand out, as Dr Porter explains. "We are pleased that the Diploma has some strong material on control systems. This is a very important area of engineering, especially for the electronics that we focus on here in York, and A-level students often have little or no knowledge of control systems."
The Department has specified its entry requirements for Diploma students. "We do ask that Diploma students complete Maths A-level as their ASL," Dr Porter says, "but Diploma students who do so and achieve high grades will be invited to interview."
"The syllabus is challenging for schools and teachers as much as for students," Dr Porter says, "and schools need to adopt new ways of teaching. But provided students have been taught well, there is no reason why they should not do very well at interviews. In fact, their in-depth knowledge of engineering and their extended projects could prove very advantageous."
Demonstrating the University's commitment to making the Diploma a success, academics from the Department of Electronics are getting involved locally, advising Diploma students at York College. "Many of the students at York College are doing very interesting extended projects," Dr Porter says. "I have spoken with a student who is working on a project in which he will put a small dynamo in the pipe going down from the water tank in his attic, generating enough power to charge handheld electronic products. There's a lot to it. He has to think about generating AC current, then converting it. He's got to think about efficiency, and ensuring that he doesn't take out so much energy that there's no pressure left in the taps."
Dr Porter thinks that the Diploma could be a great success. "The quality of teaching is all important," he says, "but there is real potential. Because the Diploma offers a new option, something different from the traditional routes, it may attract and retain people who previously would have thought engineering - or even perhaps education - wasn't for them. For the engineering sector, which often struggles with skills shortages, this is potentially very important."

Loughborough University
Loughborough University's Faculty of Engineering is one of the largest of its kind in the UK with over 4,500 staff and students across five engineering departments. Dr. Jon Petzing is Senior Lecturer in Metrology and works as the Admissions Tutor for the Wolfson School of Mechanical & Manufacturing Engineering within the University.
Jon welcomes the introduction of the Engineering Diploma, arguing: "The Diploma will increase interest in engineering amongst school students, and as a result increase numbers applying to study engineering at university. The more applicants, the more competition for places, the higher the quality of our intake."
The University has stated that Advanced Diploma students with the right grades will be accepted onto each of the six engineering degree courses offered by Loughborough, providing that they use their ASL to study Maths A-level, or in some cases a science A-level, or the new Mathematics for Engineering course alongside another qualification of similar weight.
Whilst the majority of the University's current engineering students studied for A-Levels before their arrival at Loughborough, a significant minority studied for other qualifications such as BTECs and the International Baccalaureate. "We know that individuals who have taken qualifications other than A-Levels can prove to be fantastic students," Jon says, "and we anticipate that the Diploma should produce some excellent students."
"When we looked at the Engineering Diploma," Jon says, "we saw a qualification that is a good match for our courses. No qualification will be a perfect match to a particular degree course, as there is only so

much that students can cover in the two years of the sixth form, but students with the Engineering Diploma should be well equipped to come to Loughborough. They'll have covered areas like material science and manufacturing processes which most of our other students will not have."
The University anticipates that it will start receiving applications from Diploma students in 2010. In the meantime, it is working with local consortia so that school pupils in the East Midlands area benefit from the University's expertise.

The employer view
Siemens Industrial Turbomachinery Limited
Siemens is a large international company with expertise in a range of sectors including Industry, Energy and Healthcare. Within the Energy sector, Siemens Industrial Turbomachinery in Lincoln has a workforce of 1,700 and specialises in the design, manufacture and lifetime service and support of industrial gas turbines.
Angela Borman, Collaborative Projects Officer at Siemens in Lincoln, comments: "Lincolnshire is a very rural county, and as such does not have a large base of people with engineering skills. This means we must look to develop the people we require ourselves."
Siemens has for a long time worked with local schools, for example operating the extremely successful Females into Industry Challenge. Angela sees the Company's engagement in local education as a mutually beneficial process. "By supporting schools to teach technology related subjects, we can enrich the curriculum, which is of great benefit to the pupils. Of course if our work sparks students' interest in engineering, and they go on to pursue an engineering career, then we and other engineering companies also benefit."
As Angela Borman explains, the introduction of the Engineering Diploma offers a new opportunity to expand engagement activities. "One of the many things we like about the Engineering Diploma," she says, "is that it provides students with a broad understanding of the different areas of engineering, but also an understanding of the specific types of engineering that take place in the local area. For students who choose to go on to study engineering at university, the broad understanding will be extremely useful. For those who decide to take a vocational route, such as one of our apprenticeships, they will likely have already visited our site and know what we are all about."
Siemens is now working with local Diploma consortia. The Lincolnshire East consortium is a partnership of eight schools and colleges that has been teaching the Engineering Diploma since September 2008. "One way we have helped the Lincolnshire East consortium," Angela explains, "has been by working directly with students; by having groups visit our site and also students here on work experience, we can bring engineering to life." She continues: "Another way of helping has been by working with teachers, as a sounding board for ideas. Lincolnshire being very rural, schools in the consortium are quite spread out. We have been able to offer our site as a meeting point for teachers involved with the Engineering Diploma, and I think this has been tremendously useful for everyone."
Siemens is also working with the Lincoln consortium, which has just passed through the Gateway Process and will start offering the Engineering Diploma from September 2010. Siemens helped the consortium put together their Gateway bid and is encouraging other local employers to engage with the new consortium.
The Company intends to maximise the benefit of the introduction of the Engineering Diploma. Angela says: "We are working in collaboration with the University of Lincoln to develop a School of Engineering within the University. The idea is to get local students studying for the Diploma up to Advanced Level, then continuing to study engineering at the University of Lincoln, before hopefully coming to work for us or one of the other engineering employers in the area."
Siemens efforts in Lincolnshire have been widely recognised, and Angela herself now works on a national level as a Diploma Employer Champion.

Aker Solutions E&C Ltd
Aker Solutions E&C Ltd, part of Aker Solutions ASA, is an engineering design company with its head office based in Stockton and further sites in Warrington, Whitehaven, Pembroke and Peterborough. The company employs approximately six hundred people across the UK and works in the process, water, metals, nuclear and energy sectors. An example of a project the company has recently completed is the design of a new copper, zinc and lead processing plant at the Aguas Teñidas mine in southwest Spain.
Margaret Mason, HR Advisor at the company, works at the head office in Stockton, and sits on the Employer Steering Group for a consortium offering the Engineering Diploma in Middlesbrough. "We've been very keen to get involved," she says. "When I go to careers fairs and speak to young people about engineering, in the majority of cases it's very obvious that they don't know much about our line of work.

For example, many young people think that all engineers are car mechanics. The Engineering Diploma will teach students what engineering is really about."
Margaret goes on: "The Steering Group meetings have been a real collaborative effort, with everyone chipping in with ideas and suggestions. Since the introduction of the Diploma in September 2008, Aker Solutions E&C Ltd has been involved in a number of ways. We've had students visiting the offices on work experience and working on projects. We've also sent employees to visit a school from the consortium. One of our Senior Engineers visited one school to discuss engineering, as did one of our more junior staff, who as it happened had previously been a pupil at the school herself."
Margaret argues that one of the great advantages of the Diploma is that it enables students to visit local employers and learn about the engineering discipline in which they are interested. "This is obviously great for the student," Margaret says, "but also for us as a company we can start to build relationships with people who one day may go on to work for us, either at sixteen as an apprentice, eighteen as an employee with day release or similar to study for a degree, or after university."
Margaret comments: "As always with new things, there will be some issues. For an employer like ourselves, it's difficult to accommodate a large number of students on work experience at the same time, and that's something the schools need to work around." However, overall Margaret very much welcomes the Diploma. "It's already having an impact in Middlesbrough," she says, "and I expect the cooperation between the world of education and employers will enhance the delivery of the new qualification year on year."

6. Areas for improvement

The IET supports the Engineering Diploma, but there are areas for improvement.

Public profile The Engineering Diploma has received some bad press, with suggestions that it represents a 'dumbing down' of education. This is emphatically not the case, as is evident from studying the course content or speaking with teachers and students. As previously stated, entry requirements for 79% of engineering courses at Russell Group universities state that Diploma students with the right grades and ASL qualifications will be accepted. The Diploma has been expressly welcomed by many leading universities, including Oxford and Cambridge.The engineering community has widely backed the Engineering Diploma. In addition to the IET, organisations that support the Diploma include the Royal Academy of Engineering, the Institution of Mechanical Engineers and the Engineering Professors' Council. Employers backing the Diploma include Rolls-Royce, JCB, RWE npower, BAe Systems, Toyota, Honda, Dyson, MBDA, Jaguar/Land Rover, Rosh Engineering, Boeing, and Messier-Dowty.However, the engineering community has sometimes been overly cautious about tackling bad press head on. This has left the field open to detractors, most of whom have a poor understanding of the Diploma.

Functional skills As Ofsted has recently observed3, not all consortia are delivering the functional skills component of Diploma in a coordinated manner. Insufficient links are being made between this component of the course and the Principal Learning component, particularly in those instances where these two components are being taught in different locations by different teachers. Consortia must improve in this regard.

Course availability for ASL Many Advanced Diploma students are studying for A-levels, and the new Maths for Engineering ASL option is also likely to be popular, particularly as it is being favourably received by many universities. Some new modules have been developed to serve as ASL for the Engineering Diploma, such as EDEXCEL's new aerospace engineering qualification for the Advanced Diploma. However, the range of options for ASL could be further increased. There needs to be a wider range of ASL options for students who wish to deepen their knowledge of engineering. Efforts are being made to increase the range of ASL options. The Engineering Diploma Development Partnership (EDDP) Strategy Group is looking to develop new ASL modules which would focus on specific areas of engineering, with proposed new modules including Effective Electrics, Effective Electronics, Sustainable Energy and Power, Intelligent Control, Creative Structures, Materials Innovation and Optimising Energy Systems.

Female participation In the first year of the Engineering Diploma, 7.3% of students were female. For a new qualification free from the associations of older routes into engineering, this is disappointingly low

[3] Implementation of the 14-19 reforms, including the introduction of Diplomas (Ofsted, August 2009)

proportion. Whilst central government must focus on this issue, it is also essential that consortia, teachers, careers advisors and the engineering community play their part to ensure that the proportion of female students increases in future years.

Careers education and guidance Careers education and guidance must improve in quality and quantity, in line with the increased learning options available to students following the introduction of Diplomas. Unfortunately, careers guidance has been devalued since the introduction of Connexions in 2001, and the recent transfer of responsibility for Connexions to local authorities is unlikely to address this[4].

Guidance from Awarding Bodies During the first year of the Diploma, schools and colleges report that guidance from Awarding Bodies has sometimes been tardy. Whilst some teething problems are to be expected, practices must improve year on year.

Flexibility between Foundation and Higher Levels Some consortia argue that there is insufficient flexibility to move between the Foundation and Higher Diplomas. The IET recommends that the Qualification and Curriculum Development Agency (QCDA) consider whether there are simple ways of increasing flexibility.

Towards the entitlement From 2013, students will have an entitlement to study for the Engineering Diploma. Crucially, it is important to ensure that the Gateway Process remains vigorous and to resist the temptation to drop standards in order to meet the entitlement.

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- Arshid Rafique, Lilian Baylis Technology School
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- Jennifer Wright and colleagues, Newstead Wood School for Girls
- Ian Young, TDR Training Ltd

[4] Unleashing Aspiration - the final report of the Panel on Fair Access to the Professions (Cabinet Office, 2009)

Institute of Education, University of London

The Fruits of Curiosity Call for Evidence – response by the Institute of Education, University of London.

Investing in tomorrow's talent in schools, universities and in the FE sector

6. 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?

A great deal of good has been achieved in STEM education in the past decade, particularly since the 2004 report *Mathematics Counts* by Adrian Smith and the appointment of Celia Hoyles as the Chief Advisor for Mathematics and John Holman as the National STEM Director. In school mathematics and science, teaching ('delivery') has been helped by the imaginative approaches of the DCSF and TDA who have done a better job than many had expected of increasing the numbers going into secondary mathematics and science teaching (though there are on-going issues about the shortages of specialists in both disciplines). The work of the National Network of Science Learning Centres has helped considerably in the continuing professional development of science teachers and technicians and the National Centre for the Excellence of Teaching in Mathematics is beginning to do something similar for mathematics teachers.

Longitudinal research shows that interest in STEM varies greatly among pupils and changes over time very considerably in some pupils. It is important to bear in mind that internationally we still have a fairly large number of students, both in absolute terms and as a percentage of HEI entrants, choosing to study science courses at university. Nevertheless, studies indicate that whereas it used to be the case that pupils almost always enjoyed science until some interest started to wane from year 8, increasing numbers of pupils in England as early as year 6 are losing interest in science. It is likely that this is due to them being provided with excessive numbers of boring, repetitive science lessons designed to maximise performance in the KS2 SATs.

The major barriers to ensuring that pupils feel engaged in STEM and that those with the potential progress to advanced levels in STEM are pupils feeling (i) they don't understand quite a high proportion of the science they are taught; (ii) they don't see the relevance of it. It seems likely that the new GCSEs in science introduced in 2006 may be helping with the second of these two issues (though the data are not robust). It should be remembered that mathematics is the second most popular A-level subject, biology the third and psychology (a science) the fourth. Furthermore, chemistry and physics A-level numbers are now increasing.

No progress has been made in the assessment of STEM subjects in practice in the last decade despite an increasing amount being known by researchers in the field. Inadequate notice is taken by government, by government department and by non-departmental public bodies of assessment experts and the result is the waste of large amounts of time and money and the loss of opportunities. A key case in point are the so-called 'singe level tests' where political announcements were made before any proper work had been done.

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

We lack robust data as yet on engagement but it is likely from what data we have that the same factors encourage engagement in STEM as encourage attainment – namely the quality of the teaching. Subject specialism and knowledge are important but most important is the minute-to-minute, day-to-day quality of pedagogy including the obtaining by the teacher of accurate data from individual pupils on their learning achievements and needs and the provision by the teacher to the pupil on what they need to do next to learn successfully. Such teaching is far more important than the type of school attended or even the mathematics or science curriculum studied.

There is some indication from the existing literature that out-of-school experiences (visits to science museums, playing with mechanical toys, developing an interest in natural history, having a chemistry set, microscope or telescope) may be of particular importance in inspiring some of the most capable and promising of pupils in science.

Specific suggestions for addressing challenges to attainment and post-16 participation in STEM subjects are: ensure students training to be primary teachers spend enough time learning not only the fundamentals of mathematics and science but how to teach these subjects with confidence and enthusiasm; continue to recruit the best graduates into secondary mathematics and science teaching; continue to invest in continuing professional development; do something about the looming crisis in school science technician numbers; continue to improve school laboratory science facilities (Building

Schools for the Future, etc.); get some continuity into curriculum development – at the moment the order in which key stages get revised is near random; encourage teachers to take pupils on field trips in science including, once in every pupil's lifetime, a residential fieldtrip.

One of the biggest issues we haven't yet got right is how to develop the mathematical knowledge, understanding and skills of students taking A-levels in science subjects. There has been, over the last twenty to thirty years, a tendency, especially in physics A-level, for mathematical demand to drop. This has been exacerbated by the free market that operates between Awarding Bodies as there is continued pressure on them when developing new specifications not to make these more demanding than those of other Awarding Bodies.

The work of the Foundation and Higher Level Diplomas in Science is encouraging and builds on what we have learnt about applied science at GCSE. It is not only skills that are needed but knowledge and understanding of the fundamentals of the subject. Skills fall into two main categories – those largely specific to science (e.g. undertaking a titration, using dataloggers, undertaking simple statistical tests) and those that are more generic (being able to work in a team, give an oral presentation, show initiative and perseverance; truthfulness; reliability). It is too early to say whether the Advanced Level Diploma will be successful. There are no plans for any Diplomas in Mathematics.

8. 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)?
We need teachers at all levels – primary to tertiary – with degrees in mathematics and with each of the three main branches of science: biology, chemistry and physics. That having been said, the most important thing at primary and secondary level is to have teachers who are passionate about communicating their subject and teaching pupils.
We need to reduce the impact of summative assessment on pupils, particularly at KS2 (end of year 6) and to enable teachers at both primary and secondary level to feel they are regaining their professional autonomy and responsibility. Too often teachers (STEM and in other subjects too) feel constrained by external influences (league tables, Ofsted, Health & Safety). Often such concerns are unwarranted but what is needed is a change of culture to enthuse more STEM teachers to inspire their pupils.

Institute of Physics

The Fruits of Curiosity: science, innovation and future sources of wealth
Institute of Physics response to a Royal Society call for evidence
A full list of the Institute's submissions to consultations and inquiries can be viewed at www.iop.org
11 September 2009

The Fruits of Curiosity: science, innovation and future sources of wealth
The Institute of Physics is a scientific charity devoted to increasing the practice, understanding and application of physics. It has a worldwide membership of over 36,000 and is a leading communicator of physics-related science to all audiences, from specialists through to government and the general public. Its publishing company, IOP Publishing, is a world leader in scientific publishing and the electronic dissemination of physics.
The Institute is pleased to submit its views to inform the second phase of the Royal Society's inquiry, 'The Fruits of Curiosity: science, innovation and future sources of wealth'. The response was prepared with input from the heads of UK physics departments, the Institute's Science, and Business and Innovation Boards, and from comments we have made to previous inquiries, including the RCUK Review of UK Physics.
The attached annex details our response to the questions listed in the call for evidence.
If you need any further information on the points raised, please do not hesitate to contact me.
Yours sincerely
Professor Peter Main
Director, Education and Science

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

<u>The long-term direction of policy for science</u>
1. What role should curiosity-driven research play in the UK science base in the next 15-25 years?
Curiosity-driven research has an essential role to play in the UK's science base for the considerable future. All technological advances ultimately have their origins in curiosity-driven research, where the outcomes of the research cannot be easily predicted. Such research in physics often leads to significant economic and societal benefits, usually after around a 15 year timescale from essential breakthrough in the science to the application. For example, PET, MRI, X-rays, GPS, lasers and semiconductors are all technologies that are widely used and are enormously beneficial to society; it was not so long ago that the laser was dismissed as a physicist's toy and not many people thought that atomic clocks would lead to the ability to navigate to within a metre at any point on the Earth's surface.
The UK has a strong and vibrant research base and with sufficient investment curiosity-driven research will reap significant benefits within and beyond the next 15-25 years. The importance of such research was recognised by the House of Commons Innovation, Universities, Science and Skills (IUSS) Committee in its latest report, *Putting Science and Engineering at the Heart of Government Policy*[5], where it states that: "*Curiosity-driven research is a key component of a successful knowledge-economy...[and] is one of the UK's greatest strengths.*"
However, there are pressures being placed on research council responsive mode grants, the means by which curiosity-driven research is funded, as research is being prioritised towards targeted areas and demonstrable evidence of the economic and societal impact of curiosity-driven research is being sought. It is not clear whether focusing on select, thematic areas will result in short-term economic gains, but it is obvious that in the medium- to long-term, it will undermine the UK's ability to retain the highly trained, inventive and innovative scientists and engineers who will maintain and strengthen the UK's international competitiveness. It is these people, particularly those that have been attracted to the UK by a funding system and academic ethos that allows them to pursue curiosity-driven research, who will enable the UK to respond to new discoveries for which the economic and societal impacts are manifold, but which are broader and harder to quantify than for example, profits in a manufacturing company.

[5] Putting Science and Engineering at the Heart of Government Policy;
http://www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/168/16802.htm

The RAE2008 physics sub-panel was emphatic on this point, stating in its report[6] that: *"Many of the world-leading research outputs observed in submissions originated from small responsive mode grants. The sub-panel believes that continuing availability of such grants is absolutely vital to encouraging and sustaining groundbreaking research activity. Both national and European funding agencies are concentrating heavily on large collaborative programmes which, though worthwhile in themselves, if pursued to the exclusion of smaller scale grants, may place the nation in a weak position in the future…The physics and science community cannot know where future developments will come from, and attempts to focus funding too narrowly into priority research areas (or priority departments) will limit rather than enhance the prospects of breakthroughs at the highest level."*
Therefore, the government needs to find a healthy balance between the need to fund curiosity-driven research and the translation of knowledge into products and services that can contribute to UK GDP (discussed further in response to question 15) and the need to prioritise research to address the major societal challenges such as global warming. The Institute is of the view that more attention needs to be given to where the barriers actually are within the science and innovation base, such as the lack of investment in transitional research and industrial capability that would allow the more direct products of curiosity-driven research to be widely exploited by UK companies operating within the UK.

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?

The Science Budget:

The most significant and beneficial policy has been the government's decision to double the Science Budget allowing the UK to have unprecedented support for science and innovation, which currently stands at just under £4 billion per annum. The Institute echoes the positive comments made by the 2005 International Review of Physics and Astronomy Research panel[7] which stated that: "*…[it] was struck by the general improvement in the research environment and the positive outlook of those involved with the research effort at all levels. Progress has clearly been made and the UK is now well placed to reap the benefit of the investment that has been made since the 2000 review. This progress, however, is predicated on maintaining the increased level of funding that has taken place over the last few years. The Panel cannot overstress the importance of this funding for the continued health of the subject, and for continuation of the benefits it brings to society and the economy.*"
In addition, the recent RCUK Review of UK Physics[8] stated that physics: "*…is in a generally good state of health, with departments performing curiosity-driven research of the highest international quality and having benefitted from a significant increase in research expenditure in recent years.*" Furthermore, it recommended: "*...that the UK government should continue to fund research in both basic and applied physics across a broad spectrum of subdisciplines at the level required to retain international competitiveness.*"
Therefore, the Institute wholeheartedly concurs with the recommendation of the Sainsbury Review of Science and Innovation[9] that the government continues to fund increases in basic science in line with the Science and Innovation Framework 2004-2014, and makes a firm commitment to continue do so beyond this.

Science Research Infrastructure Fund:

Another success story was the Science Research Infrastructure Fund (SRIF)[10], which provided capital funding to universities, specifically for science facilities. The third and final round of SRIF was operational in 2006-08, with the government committing £500 million. SRIF was lauded by the 2005 International Review of Physics and Astronomy Research as a key factor in improving the environment for physics research. Furthermore, the 2005 annual report of the Science and Innovation Investment Framework[11] highlighted that SRIF boosted staff morale, attracted new staff from overseas, increased student numbers at all levels, established the credibility of universities among local business communities, and encouraged greater use of facilities by SMEs. In addition, a recent report by Technopolis on the wider benefits of

[6] RAE2008 subject over reports: UOA 19 – Physics; http://www.rae.ac.uk/pubs/2009/ov
[7] The International Review of UK Physics and Astronomy Research 2005; http://www.iop.org/activity/policy/Projects/International_Review/index.html
[8] RCUK Review of UK Physics; http://www.rcuk.ac.uk/review/physics/default.htm

[9] The Race to the Top: A Review of Government's Science and Innovation Policies ; http://www.hm-treasury.gov.uk/sainsbury_index.htm
[10] Science Research Investment Fund; http://www.rcuk.ac.uk/research/resinfra/srif.htm
[11] The ten-year science and innovation investment framework annual report 2005 ; http://www.dius.gov.uk/science/science_funding/ten_year_framework

SRIF2[12] reported that: "*SRIF investments have contributed to national science and innovation policy objectives on institutional sustainability and enhanced the rate at which investment in public research is converted into social and economic benefit.*"
SRIF was discontinued and the funds became part of the full economic cost (fEC) of research allocated by the research councils, and there is some concern that this money is not being spent within universities in support of research infrastructure. Hence, a return of a similar scheme to SRIF would be welcome, particularly as it offers transparency on where funds are allocated.

Research Assessment Exercise:
One of the most significant impacts on the science and innovation base has been provided by the Research Assessment Exercise (RAE). Without doubt, it has improved the overall quality of UK research (both in terms of standards and productivity, whilst concentrating quality in fewer places), but over the years it has led to some physics departments (i.e. lower-rated as they specialised in more applied areas) to either merge with other departments or close, and has left many more departments under great financial pressures to compete with the more research-intensive ones.
This is particularly true for physics, where successive RAEs have led to a purification of the discipline within physics departments, where it is viewed solely as one that increases the level of fundamental knowledge and that when the physics is ripe for application and exploitation, the process should be carried out elsewhere, either in another department or in industry. As a result of this, research which is more applied or interdisciplinary, i.e. not considered leading-edge by RAE sub-panels, has been driven out from, or at least not encouraged to stay in, physics departments. This led the RCUK Review of UK Physics to recommend that physics departments should consider reclaiming the intellectual leadership in the broader spectrum of physics, as concerns were expressed that physics departments are over-reliant on a narrow-funding stream from the research councils.
In addition, RAE2008 revealed that, in fact, there is a 'broad' breadth of research quality throughout the UK, to the point that the research councils do not have sufficient money to fund it all, which has led to a funding system that is, at best, risk-averse and raises concerns about the long term sustainability of the research base. Therefore, either funds need to be increased or there needs to be proper planning for the future UK research base, i.e. informed and transparent debate about the possibility of condensing research into a smaller number of universities.
The Research Excellence Framework (REF), the successor to the RAE, is taking shape and increasingly looks like being undertaken in a similar manner to the RAE, i.e. peer-reviewed as opposed to being wholly led by a metrics-based approach as was initially suggested. However, it will need, in addition to continuing to recognise world-class research in curiosity-driven research, to provide explicit credit (via fully appropriate assessment criteria) of the high-quality work in the more applied/industrial and interdisciplinary areas, to reflect the wide-range of UK research effort within university STEM departments.
Finally, whether by design or not, research assessment affects the demographic structure of research in the UK, as it has the unintended effect of distorting recruitment patterns in science. Because the assessment is so important, new appointments are made of people who have an established track record, which sometimes includes staff from overseas, which can limit the number of positions available for up and coming UK researchers. To counter this, an explicit recognition of this issue could allow it to be a more positive influence, for example, in the development of the careers of young researchers and women, by including age profiles in the metrics (in addition to taking account of career breaks and/or time spent working in industry).

Merger of CCLRC with PPARC:
A major policy which has had a significant impact on UK physics research was the decision to merge the CCLRC with the PPARC to form the STFC. The financial problems that have since engulfed the STFC are well documented, so we will not revisit them here, but there are a couple of specific issues which blight the successful operation and management of its scientific programme, which if adequately addressed, could alleviate some of the pressures it is under. First, there is the issue of international subscriptions, where the STFC is paying the costs to exploit international facilities that are used by both its user community (i.e. CERN, ESO, ESA) and the wider RCUK community (i.e. ESRF, ILL). The same applies to the operational costs of UK national facilities, where the ATC and Jodrell Bank are exploited by STFC's core users and the Diamond Light Source, ISIS and the Central Laser Facility are multidisciplinary in nature. A simple solution to this issue would be that the RCUK should equally share the costs of the

[12] SRIF: a review of Round 2 and wider benefits; http://www.hefce.ac.uk/pubs/rdreports/2009/rd07_09

multidisciplinary national and international facilities. Furthermore, there is the wider issue of matching capital investment with operational costs that has not been solved by the creation of the STFC.
Second, there is the issue of currency fluctuations, where for example, membership to CERN is paid in Swiss Francs and the current weakened state of the British Pound means that increasing subscription costs are tensioned against other parts of STFC's portfolio (i.e. exploitation grants and/or funding for national facilities), which more often than not, bear the brunt of cutbacks. In some other European countries, international subscriptions are paid for by the equivalent of their Foreign and Commonwealth Offices – the UK should consider the same and let the STFC concern itself with funding and supporting world-class UK science. (Further information on this issue can be found in section 8.9 of the RCUK Review of UK Physics[13])

3. 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?
The UK has a small cadre of highly-gifted scientific individuals that make a disproportionate contribution to its progress. The UK has various schemes, such as the Royal Society Research Professorships, which identify and support outstanding excellence. These should be continued and strengthened, in line with the Sainsbury Review of Science and Innovation recommendation of attracting the best researchers to the UK from overseas[14]. In addition to optimising the leadership role of these individuals, such schemes confer freedom and flexibility. At lower levels, the relative absence of a strongly hierarchical research organisation in the universities is a strong factor in attracting the best talent to the UK.
However, the obvious danger is that if investment in UK science and innovation was to stagnate or decrease, the best UK-based scientists may consider moving overseas, particularly to the USA, following its stimulus package, to undertake research in well-funded and refurbished laboratories. The UK has recently reversed the brain drain and it will be most unfortunate to lose this talent. In addition, there is the distinct possibility that overseas students and researchers will no longer view the UK as a leading nation in terms of scientific endeavour and discovery and its universities may lose out on the fees income from overseas undergraduates and postgraduates, and on the pool of world-class researchers and technicians who may decide to seek employment in the UK's leading competitor nations. This is of particular concern for physics where recruitment is more than 50% non-UK trained people. This will not be sustained if other nations overtake the UK in scientific investment and excellence. Furthermore, the current lack of UK competition in getting these jobs may mean that local talent cannot fill the void.

4. How should science be governed to maximise benefits to society while acknowledging public questions, uncertainties and concerns?
The most important issue as far as the Institute is concerned is that irrespective of the make-up of the government department responsible for science, currently the Department for Business, Innovation and Skills (BIS), that adequate funds and support are provided to ensure that science and innovation continues to:

- be able to attract the brightest students into higher education which will lead to highly skilled graduates that make significant contributions to many sectors within the UK's economy;
- ensure academics have the freedom to undertake internationally leading research, which is the foundation for new discoveries and applications; and
- that we have the right policies and frameworks in place to transform great ideas and concepts into products and services, creating jobs, and contributing to UK GDP.

Following the 2010 General Election, it is quite likely that the machinery of government will change which may include new departments. The debate regarding a 'Department for Science', on which the IUSS Committee sought evidence to its inquiry, *Putting Science and Engineering at the Heart of Government Policy*[15], could surface again.

On this subject, the Institute is of the view that a potential disadvantage of creating a Department for Science would be the loss of the chief scientific advisers (CSAs) which would have the effect of decoupling science policy from decisions made in other departments which risks making science a distinct

[13] RCUK Review of UK Physics; http://www.rcuk.ac.uk/review/physics/default.htm
[14] The Race to the Top: A Review of Government's Science and Innovation Policies ; http://www.hm-treasury.gov.uk/sainsbury_index.htm

[15] Putting Science and Engineering at the Heart of Government Policy; http://www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/168/16802.htm

and self-contained activity within government policy. This could result in science becoming isolated and neglected in policy decisions, particularly from higher education and the innovation and business support mechanisms within BIS, possibly leading to an unnecessary competition for resources. Furthermore, there are concerns on how a standalone Department for Science would consider science education in both schools and universities. Instead of a Department for Science, in order to strengthen science in government, the Institute concurs with the Royal Society of Edinburgh[16] that: *"a strong strategic capacity is required at Cabinet level to maintain the strength and applicability of UK science and to ensure that it is effectively exploited across Government."* Therefore, we support the IUSS Committee's recommendation that the Government Office for Science should be moved to the Cabinet Office[17].

Furthermore, the departmental CSA principle should be built on, which has the potential to ensure the effective implementation of cross-cutting policies. More people with science backgrounds should be placed in the policy units of government departments, either through an expansion of the offices of the CSAs, or preferably, the incorporation of science-trained workers in each departmental policy unit.

Whatever the outcomes post the 2010 General Election, there will be a need for science and innovation to continue to be a priority area, and for there to be close linkages between science and innovation with higher education in an overarching strategy as there is currently in BIS. The only issues we have with the formation of BIS, and its predecessor DIUS, was that under the former DfES, education and higher education, parts of the same pipeline, were under the same department, and that despite the creation of both DIUS and BIS, there seems to be little coherence between HEFCE and RCUK policies. It is difficult to comment as to what impact the separation of these two important functions has had, but there needs to be a coordinated effort to ensure that there is joined-up thinking between the two as they clearly overlap with one another.

In relation to public uncertainty, etc., the learned societies, such as the Institute, have an important role to play in countering the lack of public trust and confidence in science and engineering by providing scientific advice which is clearly independent and objective. As already mentioned, a weakness of the current system is that there are low levels of science-trained people employed in higher levels of government, and this has an impact on the government's ability to formulate and regulate science policy. The situation could be improved by the introduction of a STEM stream within the Civil Service. Within this, it would be very important that the entry requirements for graduates entering the stream were high to ensure sufficient quality (as with other specialist steams). The training for staff in the stream would include a significant element of economics, statistics and the social sciences – these are the core skills for evidence-based policy-making in government, and staff would build on their existing scientific training.

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

The long term social and cultural impacts of scientific research can be measured in a number of ways based on the RCUK definition of economic impact[18]: *"…Impact embraces all the extremely diverse ways in which research-related knowledge and skills benefit individuals, organisations and nations by fostering global economic performance, and specifically the economic competitiveness of the UK; increasing the effectiveness of public services and policy; and enhancing quality of life, health and creative output."*

The societal impacts of physics research are limitless, and no doubt the same applies to other STEM disciplines. But a major impact that is often overlooked is the production of highly trained workers – people that are trained though curiosity-driven research are able to provide industry the capacity to exploit and build on the results of this broad base of research. Skilled workers are essential both in the industries where this knowledge is applied, and across the UK's economy. For example, physics graduates can be found all over the business, industry and engineering communities adding immense value to their companies and the exchequer.

The current practice of requesting academics to predict the economic impact of their work is flawed. Serendipitous discovery via curiosity-driven research has led to many technological step-changes that have revolutionised our lives today, such as MRI scanners, GPS technology and so on and so forth. The prediction of the best prospects for future discovery and invention is notoriously difficult, hence it is essential for the UK to support a broad research base and not attempt to pick winners based on economic impact prediction.

<u>Investing in tomorrow's talent in schools, universities and in the FE sector</u>

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[16] Royal Society of Edinburgh Advice Paper (09-01) January 2009; http://www.royalsoced.org.uk

[17] Putting Science and Engineering at the Heart of Government Policy; http://www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/168/16802.htm

[18] Including Economic Impact in Funding Applications; http://www.epsrc.ac.uk/ResearchFunding/Changes/EconomicImpact.htm

6. 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?
The past decade has certainly seen a great deal of change in education, particularly in the STEM area and especially in schools and colleges. The higher education sector, while undergoing massive change in the research area and also being subjected to an extensive quality regime in teaching, has curiously changed correspondingly little. Whether all these changes have led to progress is not clear. Some of the issues that have emerged will be discussed in more detail in response to question 7.

Before dealing with the individual sectors, it is worth considering a few overarching areas of importance:

Teachers:
One very important change in the last decade has been the acceptance by government that there is a serious shortage of teachers in some STEM subjects, particularly mathematics and, most serious of all, physics. For many years, while teachers in schools and colleges were classified as science teachers, the problem was swept under the carpet. By accepting that specialist biologists, chemists and physicists are required, the government took a major step forward and, while these problems are a long way from being solved, there is every indication that they are being taken seriously and there are a number of activities that have been designed to try to ameliorate the problem. The government has also shown a laudable tendency to be more open and to work with partner organisations, including learned societies, for example, through the SCORE partnership.
Also in the last decade, there has been a greater acceptance of the need for subject specific CPD, most notably via the creation of the National Science Learning Centre and its mathematical equivalent, the National Centre for Excellence in the Teaching of Mathematics (NCETM), and the network of science learning centres. However, welcome as these changes have been, there is still a need for teachers to be incentivised to take advantage of these facilities. At present, it is only the professionalism of the teachers that is driving the take up of CPD and many of the teachers that need it most are quite reluctant to take advantage. One way to address this problem is to take the CPD to the teachers, which is the approach taken by the Institute in its *Stimulating Physics Network*[19]. However, what is required is either some sort of professional requirement to undertake subject specific CPD (the learned societies could play an accreditation role here) or a material benefit for having done so.

Standards:
The IUSS Committee's recently published report, *Students and Universities*[1220], addresses, amongst other issues, the need to look at standards in the higher education sector. The Institute is in broad agreement with many of the recommendations of this report and will not repeat them here.
In schools and colleges, the issue of standards has been one of great and continuous debate over the last decade, particularly in the context of GCSEs and A-levels. Curiously, there has been rather less debate in Scotland on the subject of Highers and Advanced Highers. The Institute feels that much of this debate has not been conducted at a very high intellectual level; frequently, government is criticised both when pass rates rise, seen as evidence of easier assessments, and when they fall, which is seen as poorer performance. As a result, everyone involved becomes defensive and there is little sensible debate on what really are the key issues, which is the purpose of the various qualifications and whether they are fit for purpose (this matter is discussed further below).
The Institute does not wish to become embroiled in the rather futile argument about the fall (or otherwise) of standards over time. Inevitably, qualifications, assessments and teaching methods change over time and it is not possible to gauge standards simply by looking at old examination papers as some would have it. We would, however, like to make one point on the issue, which is that it is very hard to think of any drivers or incentives in the system that serve to maintain standards while there are many that appear to risk the opposite. For example, schools are rated by league tables based on examination performance; pupils seek the best grades for university entrance; and universities like students to get the best grades for entry to raise the status of the institution. Even the awarding bodies, in a commercial market, will often sell their course according to the percentage of students that achieve top grades. Beyond the relatively light touch of the QC(D)A, where are the equivalent drivers in the system to maintain standards?

[19] Stimulating Physics; http://www.stimulatingphysics.org/overview.htm
[20] Students and Universities; http://www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/170/17002.htm

Science for the Citizen vs. Scientists of the Future:
A recent theme in education pre-19 has been the introduction of the 'how science works' component into GCSEs and, more recently, A-levels. There are two strands to the thinking. First, there was good evidence that students were being put off science because they were not able to engage with it as they could with many other subjects, and answers were either right or wrong and there was no room for debate or in seeing the relevance of science to everyday life. It is too early to see if the new specifications have been successful in persuading more people to stay with science at A-level but early signs are encouraging. Second, there was a need to raise the general level of appreciation of the importance of science in society for all students. This is certainly a laudable goal, although one not readily susceptible to measurement. But sensible as these goals are, there is a potential risk that the students best suited to science are not being sufficiently challenged neither for their own satisfaction nor for the requirements of higher education admissions tutors. This is undoubtedly a major challenge for the future.

Turning now to the various education sectors:
Primary:
The UK, or England, at least has been portrayed as an international leader at the primary level, largely as a result of introducing national testing at key stages 1 and 2. The appearance of science in these tests seems at first sight to be, therefore, a good thing. However, the time spent drumming into children particular chunks of knowledge would actually be better spent making them familiar with the notions of the approach of science, with hands-on authentic experiences that show the power of science. There is currently a review of primary education and it remains to be seen how that will turn out. But it seems unlikely that there will be a move too far away from a specific, fact based curriculum. The role of STEM education at this level should be to excite and whet the appetite.

11-16:
There has been almost constant change in this sector over the last 10 years or so, with curricula changing in an uncoordinated manner and change introduced, usually without adequate piloting. One of the reasons that the new style GCSEs have been so controversial is that many teachers found that the skills they required for the how science works components were different from their traditional areas of expertise and they did not have time to learn the new ways of teaching. Similar remarks could apply to some of the specifications developed by the awarding bodies on a very tight timescale.
National testing at key stage 3 has also led to change. First, it had the positive effect of raising minimum standards but there have been two major negative effects. Second, the extra assessment has meant that there is less time for teaching and learning as well as contributing to the general regime of over assessment. Third, there has been a tendency for teachers to 'teach to the test', that is to have a reluctance to go beyond material that is to be assessed. Given that the key stage 3 tests were more to do with minimum than maximum standards, this is a serious flaw. It is noticeable that this is now the area where there is an increasing division between the state and the independent sectors.
A recent initiative has seen the government move to try to encourage schools to offer more triple science GCSEs to the more able students. The Institute broadly approves of this approach, with a few reservations. One is that it does mean that there is an even greater need for a specialist physics teacher at GCSE level; many schools simply do not have such a person. Another issue is that, often, triple science is taught in a double science slot, for administrative convenience than educational benefit. It may well be that a better approach would be to keep all sciences to key stage 3 but then to allow students to drop one or more of them for GCSE. While that may seem a retrograde step, it may well be that it would lead to a greater commitment to the subject and greater take-up at A-level.

16-19:
Compared with the radical changes in the 11-16 curriculum, the post-16 sector has been relatively stable in recent years, although there is a major issue around the whole area of applied and vocational education, including the introduction of the diplomas (discussed further in response to question 7).
The major change to A-levels occurred just about a decade ago with the introduction of Curriculum 2000 and the advent of the AS-levels as an assessment point after one year. While there have been a few benefits to students with this approach, allowing a little more flexibility to take a broader range of subjects, the negative effects far outweigh the positive. Specifically, the AS examinations have taken huge chunks of time out of the curriculum and have led to a culture of over-examination that has been exacerbated further by many students resitting modules on a regular basis. With many schools and colleges allowing lesson-free revision time in preparation for the AS examinations, and in some cases even for the resits, the time lost has been considerable. The Institute believes that, while there is a place

for stand-alone AS-levels, the broad model of Curriculum 2000 is flawed and should be reviewed as a matter of urgency.
A report commissioned by SCORE[21] has demonstrated that there is a considerable range across the relative difficulty of A-levels, and other post-16 qualifications, with the sciences and mathematics among the most difficult. With the exception of the special case of General Studies, Physics emerges as just about the hardest of all. The negative consequences of this range of difficulty are only too obvious in these days of school league tables and UCAS points tariff, both of which implicitly assume an equal standard for all A-levels. It is no surprise to see that the fastest growing A-level subjects are among those with the least difficult assessments. (Note that it is not the subjects themselves that are intrinsically easier.) The Institute has strong qualitative evidence that teachers, parents and pupils are acting to take people from physics A-level and move them to 'easier' subjects. And yet, government and the QCA deny explicitly that there is any difference in standard. While this is undoubtedly a difficult area, it does no favours to anyone for the government simply to deny there is an issue. The problem is made worse by having more than one awarding body; not only are there no effective mechanisms in place to compare the difficulty of different subjects, there are also none that compare the same subject between the different specifications.
Given what we know about the relative difficulty of A-level subjects, it seems almost paradoxical to learn that the most common complaint from higher education admissions tutors in physics and engineering subjects is that the entrants' knowledge is lower than it used to be. Some of the reason for this is that the students have a broader range of skills than they used to, particularly in the ICT area. But there is a specific problem in the mathematical content of A-level physics. Broadly, in order to allow physics to be a stand-alone A-level, a great deal of the mathematics has been removed. Not only does this make the physics less satisfying, it also means that students do not actually realise the nature of the subject and it certainly means that they are not adequately prepared for university entrance (discussed further in the following section). The Institute strongly believes that some sort of A-level physics qualification should exist that allows the subject to be described with the appropriate level of mathematics.

Higher Education:
This is the sector that has experienced least change over the last decade, at least in terms of curriculum and teaching. Indeed, given the changes that have occurred in schools one could say that this relative stability, or conservatism, has been a weakness and that, instead of just complaining that the incoming students are not sufficiently well-prepared, university departments should be adjusting their courses to meet the abilities of the students. For a number of reasons, the tendency has been, in physics at least, to try to maintain the standard of the graduates, which has meant more material being stuffed into the curriculum. This appears to be a significant problem. Either we accept that degree standards should fall, which universities are reluctant to do, or we continue to provide unsuitable courses for nominally well-qualified entrants. Some of the most prestigious universities already match their first year programmes to entrants with knowledge above A-level, which tends to provide an advantage to students from the independent sector, where their specialist teachers may have taken them further.
A major factor in the higher education sector in the last decade has been the ongoing Bologna Process for the reform of higher education in Europe. Across much of the rest of Europe, this has led to major structural change in higher education. One area where the UK is out of line with the process is in the route to a PhD where, across most our European competitors, the 3+2+3 model has been adopted. The QAA has asserted that the UK system is consistent with the Bologna model, so there will be no pressure from government or HEFCE for universities to change their systems. However, there have already been cases of UK graduates with four-year integrated Masters qualifications, such as the MPhys, not being accepted for a PhD in another European country and there is an increasing number of UK academic positions being taken by scientists who have not been educated in the UK. Potentially, this could lead to serious problems in the future by which time it may be too late to act.
Within the last decade, there has also been a major expansion of university places; very few of these have been in the STEM area. Physics numbers, for example, have stayed flat over this period, while subjects such as psychology, drama and media studies have soared. It is hard to understand a higher education market that is driven solely by the choices of students who have little or no information about career prospects and employers' needs. If this market is to be viable, there is an urgent need for an 'independent' guide to the medium- to long-term career prospects for graduates of different subjects.

[21] Relative difficulty of examinations in different subjects; http://www.iop.org/News/file_30371.doc

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

Primary:

As discussed previously, the main task is to decide the purpose of primary science education. It is our view that the most important aspect is to introduce children to the notion of science, what it is and how it works, providing them with real experiences and emphasizing that it is about discovery and that scientific fact is rooted in observation; too much science is presented as a set of facts to be learned as rules, as opposed to understanding the principle of proposing a hypothesis and then validating it by proper testing.

A significant problem in the primary sector is that very few of the teachers have a STEM degree and almost none of them have a physics degree. This leads to substantial problems and it is no exaggeration to say that, for example, the majority of primary school teachers do not understand Newton's laws of motion or how electricity works; topics that they are expected to teach. It is entirely likely that young children are being seeded with incorrect notions that will cause them problems later on. There is perhaps a need for an audit of teacher knowledge in these areas, together with a programme of subject-related CPD, which is not common at this level.

Secondary:

There are many significant challenges facing the secondary sector. One of the most recent changes has been the introduction of the new diplomas and, in particular, the proposed science diplomas, which have proved controversial. The Advanced Science Diploma is still under review, after the decision to delay its implementation by a year. Nonetheless, current indications still seem to show that there is an uncertainty in the purpose of this diploma. On the one hand, the government is keen to remove the stigma associated with vocational routes through education, which is entirely laudable, but on the other, by insisting on a one-size-fits-all character for the Advanced Diploma, they make it difficult for students with the qualification to advance to physics and mathematics courses in universities, for example.

Assuming that the Phase 4 Diplomas go ahead, which is by no means certain if there is a change of government, there will be significant challenges for schools and colleges to offer them in parallel with the existing A-levels and other qualifications. Given the well-known and severe shortage of physics specialist teachers, the Institute is extremely concerned about the extra load, not to mention the additional administrative burden of setting up teaching consortia, etc. One is drawn reluctantly to the conclusion that the science diplomas have been created for political rather than educational reasons.

It is unlikely that the diplomas will have much currency in the independent sector. This single fact alone will almost guarantee the continuing existence of A-levels but it is also a symptom of a more general trend for the independent sector to drift away from the assessment regimes used in the state sector. Many independent schools and colleges offer the IGCSE instead of the standard versions and the arrival of the Cambridge Pre-U may lead some of them away from A-levels. Inevitably, the leading universities will take note and there is a very real danger of the division between the independent and state sectors becoming wider. Given that science subjects already draw proportionally more students from independent schools than is average for all subjects, this would be highly regrettable.

Employers state that, not only is there a need for more STEM graduates, but there is an even greater need for more people at the technical levels, usually sub-graduate. The diplomas are, in some sense, an attempt to rectify this situation and whether they do so remains to be seen. What is clear is that applied and vocational routes for students not wishing to go to university are vitally important and some people have expressed concern that the diplomas may actually result in some of these pathways disappearing. A major problem in this area in the UK is that academic degree routes are perceived as having higher social status than educational qualifications that lead directly into employment. No amount of advertising of diplomas is going to change that perception, which is reinforced by the qualifications offered by the independent sector; it is deeply embedded in the UK culture and is a very serious challenge indeed for the future.

Tertiary:

The major challenge for STEM subjects in universities is to maintain standards while increasing the breadth of entry, particularly in terms of socio-economic status and, for physics and engineering, gender. A particular problem for STEM subjects is that a certain knowledge and skills base is assumed on entry; aptitude and ability are necessary but seldom sufficient by themselves. Some universities have combated this problem by the use of a foundation year, which can work well but has substantial financial disadvantages for students.

The last 10 years or so have not been kind to many departments in STEM subjects, particularly in physics and chemistry, where a substantial number of departments have disappeared (around 30% in physics),

leading to 'deserts', i.e. regions in the UK, such as East Anglia, where students have no access to undergraduate physics and/or chemistry degrees. The reasons for the closures have been largely financial, driven partly by the consequences of the RAE and by the fall in the unit of teaching resource. Both these issues have been alleviated to a certain extent. For example, fEC has meant that expensive research subjects have tended to benefit proportionately more. In teaching, HEFCE has increased spending in certain STEM subjects, including physics and chemistry, by about 20%, to cover the shortfall identified in studies commissioned by the Institute[1422] and the Royal Society of Chemistry. As a result, many physics departments are breaking even, or better, for the first time in a decade. Some others, however, still struggle to make ends meet.

As already mentioned in response to question 2, there has been much recent speculation about how many research-intensive universities it is sensible to support; the Russell Group has mentioned a number between 20 and 30 and the research councils have commented that there are too many applications for the funds available. Research funding is discussed elsewhere but an important point for teaching is that, if the number of universities carrying out research is reduced, how will the demand for undergraduate teaching be satisfied? There is currently no viable financial model for a department of physics to survive without research income. There is also a question of whether it is a good idea for undergraduates, particularly in the later years, to be taught by scientists who are not research-active. If it so happens that there is a concentration of research into a much smaller number of universities, it will be a major challenge to ensure that the supply of graduates is not affected.

Another challenge will be the long term effect of tuition fees on the uptake of STEM subjects, at the postgraduate level in particular. At present, it is too early to tell and the downturn in the economy has obscured any possible decline but this is an area where it will be necessary to monitor the situation carefully.

Another major challenge for STEM is how to accommodate the increasing multidisciplinarity of research while maintaining the essence of the disciplines that make them so valuable to bring together. The Institute believes that, while subjects will always be fluid to a certain extent, for the foreseeable future, it is essential to maintain the identity of disciplines. Broadly, physicists do not think like biologists, who do not think like engineers. None is better but all are necessary. The danger will be for courses to lose their identity, which could have serious long-term consequences. An experiment is taking place at present with the introduction of interdisciplinary doctoral training centres. It will be interesting to see if this model of postgraduate teaching fulfils its early promise.

8. 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)?

As already touched upon in response to question 6, in schools, the major issue is undoubtedly the shortage of suitably qualified physics teachers. Until recently, the government did not accept there was a need to distinguish between the different specialisms of science teachers. Now, they do and, following work sponsored by the former DfES and a series of reports from Smithers and Robinson at the University of Buckingham[23], it has been accepted that physics specialists, at best, form only 19% of the science teaching workforce. Furthermore, the age profile of the teachers is such that many of them will retire over the next few years. To put the matter into perspective, the government's own targets require around 750 new physics specialists to enter the profession per year; current recruitment is less than 400, and not all of those go on to become teachers. This level of recruitment is not even enough to maintain the *status quo*.

In response to this shortage, the DfES/DCSF and TDA have set up a number of schemes to increase the number of physics specialist teachers. Although some of these do involve attracting physics graduates from other professions, the two principal ones involve providing either a knowledge booster course preceding PGCE training, the *Physics Enhancement Programme*[24], or retraining existing biology teachers to teach physics, the *Science Additional Specialism Programme*[25]. The Institute is heavily involved in both these programmes, although, particularly in the latter case, there are issues concerning the definition of a specialist teacher. Nonetheless, such initiatives appear to be the only plausible route to remedying the shortage of teachers.

One area where possibly more could be done is that we know that many physics graduates are put off teaching by the requirement to teach biology and chemistry to students in their early years. A much more natural combination would be with mathematics. In fact, it is now possible to train as a teacher in physics

[22] Study of the Finances of Physics Departments in English Universities; http://www.iop.org/activity/policy/Publications/file_21216.pdf
[23] The University of Buckingham staff publications and conference papers http://www.buckingham.ac.uk/publicity/academics/acadpub.html
[24] Physics Enhancement Programme; http://www.gatsby.org.uk/pep.html
[25] Science Additional Specialism Programme; http://www.iop.org/activity/education/Teacher_Support/sasp/page_33328.html

and mathematics (at the University of Warwick) but the barrier appears to be at the school level where management structures appear to preclude the joint teaching of the two subjects.
In most other sectors of the economy, a shortage of people would mean that the market would adjust to pay more to those in the shortage subjects. The nature and organisation of the teaching profession make this type of differential pay less than straightforward to apply. Both school senior management teams and trades unions appear to be opposed to the idea, partly because they see it as creating divisions between people doing essentially the same job. One alternative would be for government to cover the loan repayments of any specialist teacher in a shortage subject who remained in the profession. This would have the dual benefit of offering a small element of differential pay while leaving school management structures intact; the benefit could also be tied to the graduate remaining in teaching and should therefore help retention.

Building and sustaining research careers

9. 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?

The 2008 annual report of the Science and Innovation Investment Framework[26] stated that on the number of researchers in the workforce, the UK performs less strongly, and is sixth in a list of G7 nations. There has been little change in the UK's performance over the last decade. This is of concern as training and retaining more UK-based researchers, and attracting researchers from overseas, particularly those who are physics trained, will be crucial for the future prosperity of the nation.
Of all disciplines, physics has one of the highest rates of continuation of education at the postgraduate level. Many physics graduates choose to study in other areas, such as meteorology, environmental science, engineering, etc. The increase in stipends, thanks to the Roberts Review[27], and the extra flexibility introduced by the doctoral training accounts has led to a considerable improvement in the lot of postgraduate students in recent years. Generally, physics has a high PhD completion rate and doctoral graduates have good career prospects outside academia. It is worth noting that, because the more exotic, leading-edge areas of physics often attract the most able postgraduate students, PhD graduates from these areas are often in the highest demand from employers.
In the international context, however, there is a general feeling that UK PhD graduates are between one and two years behind their counterparts in other major industrialised nations; this has implications, particularly in light of the Bologna Process (see response to question 6 for further details) that could affect the mobility of UK graduates to work and study in mainland Europe, as they could be discriminated against on the basis of their qualifications. It is essential that this issue is addressed before the academic career prospects of UK-educated PhD graduates diminish to the point of affecting the recruitment of postgraduate students.
In the last 5-10 years there has been an ongoing and significant shift towards the employment of overseas research assistants (RAs) instead of those trained in the UK. This shift has almost certainly improved the quality of UK research but it does raise some concerns about future leadership in the UK if these people choose not to stay after completing their projects.
In general, RAs have not been treated well in university departments. The Institute's *Women in University Physics Departments*[28] site visit scheme highlighted many of the problems, which included very poor provision for career guidance. It is hoped that initiatives such as the Institute's *JUNO Project*[29] and the revised RCUK Research Careers Concordat will contribute to major improvements. One area that has been very successful has been the various research fellowships offered by the Royal Society, the research councils, etc., as well as the fellowships that emerged following the recommendations of the Roberts Review. These have given high-quality researchers an opportunity to kick-start their careers, allowing them to spend several years undertaking research before becoming involved in teaching and administration.
Unfortunately, as these Fellows have been popular recruits for permanent positions, not least due to their personal funding, other RAs have suffered diminished prospects. While, in one sense, this is inevitable given the few academic jobs available, it is nonetheless the case that some RAs working on long-term projects are employed on a series of short-term contracts; there is a need to develop a permanent career

[26] Science and Innovation Investment Framework 2004-2014: Economic Impacts of Investment in Research & Innovation - December 2008 ; http://www.dius.gov.uk/science/science_funding/ten_year_framework
[27] SET for success; http://www.hm-treasury.gov.uk/ent_res_roberts.htm
[28] University Site Visits; http://www.iop.org/activity/diversity/Gender/Diversity_and_academia/University_site_visits/page_25130.html
[29] Project Juno Code of Practice; http://www.iop.org/activity/diversity/Publications/file_25741.pdf

path that recognises their vital contribution. For other RAs that perhaps are less suitable for research, there is a need for better, disinterested careers advice.
On this point, the RCUK Review of UK Physics[4] stated that due to the high numbers of physics RAs compared to other disciplines, there is a lack of sufficient careers advice provided to them and that there is a need: "*…for universities, Funding Councils and Research Councils [to] work together to develop the research concordat, so that realistic career advice is given to junior researchers, and that mechanisms to ensure early career opportunities are maximised in strategic areas of the research base.*"
Almost a half of new academic appointments in the last few years have been overseas physicists who have not been through the UK educational system. This situation undoubtedly reflects the high quality of UK physics as well as the flexible, meritocratic appointments procedure. The appointments also probably raise the standard of research. However, there are potentially devastating consequences on the ambitions of young UK scientists. The international flavour of departments in part reflects the global character of the discipline but there is evidence that the influx of overseas physicists is not matched by a corresponding rise in the number of UK nationals obtaining posts in other nations.
The research councils, EPSRC in particular, have taken care to encourage academics early in their careers, with specific programmes for those who are making their first applications. However, STFC tends to fund large research teams and even EPSRC is indicating that it would like to fund larger programmes over longer time periods. This approach is probably sensible but it does make it much more difficult for new researchers to make an impact and to develop a portfolio of grants to build up their reputation.

10. What sorts of incentives can we develop to keep talented students and postgraduates in science?
The issue of retention and attrition of ethnic minority students has been explored by the Institute jointly with the Royal Society of Chemistry in the production of two reports; *Representation of Ethnic Groups in Chemistry and Physics*[30], which charted the progress of all ethnic groups from GCSE to postgraduate level, and *Why choose physics and chemistry?*[31], which looked at the influences on physics and chemistry subject choices of black and minority ethnic (BME) students.
The following recommendations based on the findings of both reports, although aimed primarily towards BME students, can be extrapolated to apply to STEM students of all backgrounds:

- Enjoyment of physics and chemistry:

Focus on increasing the enjoyment of young ethnic minorities studying physics and/or chemistry at school, especially females, and illustrate the relevance of the subjects to everyday life. Appropriate intervention for school pupils might include the provision of opportunities for (exciting) practical work in universities, science centres and industry where at the same time students would have the opportunity to meet working physicists and chemists to discuss with them their work in context. Such opportunities should be provided regularly, not as one-offs. Teachers play a vital role in enthusing students, so providing teachers with CPD opportunities to revitalise their enthusiasm and interest in physics or chemistry is also essential.

- Careers information:

Provide comprehensive information to young people and their families regarding the range of options available to physics and chemistry graduates, the quality of such career options, the demand for such graduates by employers and the potential financial rewards.

- Role models:

Highlight role models who show ethnic diversity among those people employed in physics- and chemistry-related careers.

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?
The career-track model needs to take greater account of the needs of women researchers, and others who choose to take a career break, for instance, maternity leave, etc., and young researchers. As previously mentioned in response to question 2, the pressures imposed by the need to excel in the RAE

[30] Representation of Ethnic Groups in Chemistry and Physics; http://www.iop.org/activity/policy/Publications/file_8863.pdf
[31] Why choose physics and chemistry? The influences on physics and chemistry subject choices of BME students ; http://www.iop.org/activity/policy/Publications/file_36117.pdf

have led to universities making more conservative appointments to appoint experienced researchers to fill academic positions, thus discriminating against young researchers and women. Indeed, an increasing number of appointments have been made of established overseas staff, which limits the number of academic positions available for up and coming UK researchers. In physics, the average age of appointment to lectureship posts is around 35. Many persons appointed have been research associates or held a personal fellowship in a different university from the one in which they get their permanent appointment. Thus, to be appointed, a candidate must both have an excellent academic record from the time of graduation and usually be prepared to move either from one area of the UK to another or to a leading overseas laboratory. This means that it is extremely hard for a woman to be appointed unless she is prepared to delay starting a family until her mid-thirties. This problem could be mitigated by requiring university departments to provide a plan of how they intend to ensure appropriate levels of diversity among staff that they will submit to the REF (currently scheduled for 2013).
On the issue of people exchange between academia and industry, this is something that was recommended by the RCUK Review of UK Physics[32] where it was stated: "*…that DIUS and RCUK work together to develop mechanisms which enable the easy flow in both directions between industry and academia (though this point is not specific to physics).*"
In keeping with this, we need to make the boundaries between the private and public sectors more 'porous' so that there is a better exchange of people and hence information. A system that encourages academics to be seconded to industry for short periods and for industrialists to go into universities to explain their needs and requirements should be developed. However, the skill sets of an academic will differ from those of an industrialist, so care must be taken to offer roles that will be appropriate and meaningful (an issue discussed further in response to question 12).

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?

To strengthen science and innovation across the private sector in the UK, it is necessary to first acknowledge the impact that science currently has on the UK economy. Industries ranging from banking and retail to aerospace and pharmaceuticals are dependent on physics research and expertise, and physics-based industries contribute more than £70 billion to the UK economy[33]. Beyond this, physics-trained people and physics knowledge can be found in all sectors of the economy; for example, the Royal Society's recent report, *Hidden Wealth: Science in Service Sector Innovation*[34], has described the importance of STEM knowledge and STEM-trained workers to the service sectors. The knowledge generated in the science base is not easy to track, but has substantial and broad benefit to the economy, and the absence of this 'seed corn' knowledge can have long-term detrimental effects[35]. As such, the primary means by which science and innovation across the private sector can be strengthened are by building on the research base and increasing the number of STEM trained workers in the general population.
To further improve the progression of this knowledge and expertise to the private sector, there is a need for a renewed focus on enabling people to move freely between the two sectors. It is acknowledged though programmes such as Knowledge Transfer Partnerships (KTPs) that people are the most effective form of knowledge exchange, however, in terms of career progression in both academic and industrial settings, time spent away from a 'primary' role can be detrimental, particularly regarding the academic requirement for a continuous publication history that may not be possible within industrial settings. In keeping with the issues raised in relation to academic career paths in response to question 11, there should be a drive towards greater flexibility, promoting a diversity of backgrounds and career paths within academia. In terms of how 'people exchange' could practically be accomplished, it is useful to look at a different form of knowledge exchange: direct, project-driven collaborations between companies and university departments, which have made significant steps forward over the past decade, coinciding with the implementation of the recommendations of the Lambert Review[36]. One of the major recommendations of the review was the creation of templates for formal agreements ('Lambert

[32] RCUK Review of UK Physics; http://www.rcuk.ac.uk/review/physics/default.htm
[33] Physics and the UK economy; http://www.iop.org/activity/business/Business_and_Innovation_Policy/Publications/economy/page_29809.html
[34] Hidden Wealth: Science in Service Sector Innovation; http://royalsociety.org/page.asp?id=8691
[35] The economic benefits of publicly funded basic research: a critical review; in3.dem.ist.utl.pt/master/03econ/lecture_6.pdf
[36] Lambert Review of Business-University Collaboration; http://www.hmtreasury.gov.uk/lambert_review_business_university_collab.htm

Agreements') between companies and universities[37], so promoting best practice and removing procedural hurdles. Interestingly, some evidence suggests that the take-up of these formal templates has been relatively low, and partners are instead using the 'decision guides' incorporated into the agreements as starting points for discussions aimed at producing more flexible and tailored arrangements[38]. In the same way, while formal Lambert-style agreements for staff exchange (an area where flexibility is essential) would perhaps not be useful, the 'decision guide' aspects of the Lambert Agreements could be replicated and adapted for joint employment or secondment purposes. These guidelines would enable those companies and university departments which have not previously operated secondments to be able to create agreements in good time, and with the necessary legal safeguards, so allowing staff and academics greater freedom of movement. Of course, beyond the procedural aspects, this will require willingness on behalf of both businesses and universities to buy into the scheme, and an understanding of the cultural barriers that both sides will need to overcome.

Finally, it should be emphasized that the exchange of knowledge and people should not just be between the academic and private sectors, as there is an urgent need to build on the low level of knowledge exchange between the private sector and other areas of the public sector, such as government. It is notable here perhaps that, despite championing them, the government doesn't currently use the Lambert Agreements to facilitate this exchange. As mentioned in response to question 4, there should be a programme of secondments of senior private sector researchers and academic scientists into government specialist positions. Such fixed-term appointments would allow scientific advice in government to be more independent and up-to-date, and may also have the advantage of proving attractive to mid-career high-flying staff.

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

The UK's overall R&D investment is low compared with other OECD countries[39]. In terms of R&D intensity, the UK spent 1.8% of GDP in 2005, significantly lower than Germany and France, and a long way from the UK's 'Lisbon target' of an R&D spend equal to 3% of GDP (and well short of the revised UK target of 2.5% of GDP). A report from the Institute has shown that the level of R&D spend in the physics-based sectors of the economy dropped by 15% between 2001 and 2004[40]. There are some indications that the current recession has had the effect of driving down R&D in all sectors and this is of great concern to the future of UK science-based businesses, and for the future of the UK as a knowledge-based economy. However, recent work by NESTA has suggested that this low figure is not representative of all sectors of the UK economy, and highlighted strengths in aerospace and the pharmaceutical industries. NESTA has also worked to raise the profile of the breadth of innovative activities in the UK economy, which are science-based but not currently captured by R&D statistics[41], with a view to developing a broader measure of the innovative activities of the UK; the 'Innovation Index'[42] project is planning to report early next year. There has been recent movement within government away from such a widening of the definition of R&D used in metrics and the Institute is of the view that any broader focus should not detract from the impact of science on the wider innovation landscape. Science underpins the technologies which enable this innovation, and science-trained workers are often those which are best equipped to undertake innovative and technologically challenging activities. To shift focus away from science would have a detrimental effect on innovation across the UK economy.

Focusing on the recent declines in some areas of R&D, to strengthen indigenous R&D and innovation in physics-based companies, the reasons that R&D is in decline and why companies choose to relocate overseas needs to be better understood. One of the key reasons for companies, particularly smaller businesses, but also some larger companies, choosing not to conduct R&D is the level of risk that must be undertaken.

One means of mitigating such risk that is permissible within state aid rules, is by providing the confidence of a strong market for a final product and through innovative procurement strategies where the government can act as a 'lead' consumer to benefit science-based companies of all sizes. This 'demanding innovation' doctrine has a key role to play in stimulating and supporting R&D-intensive businesses as the UK comes out of recession[43] and can be seen in two parts: first, the state as a lead

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[37] Lambert Tool Kit; http://www.dius.gov.uk/innovation/business_support/lambert_agreements

[38] Streamlining University/Business Collaborative Research Negotiations; http://www.dius.gov.uk/reports_and_publications%20HIDDEN/streamlining

[39] Main Science and Technology Indicators (MSTI): 2009/1 edition; http://www.oecd.org/document/26/0,3343,en_2649_34451_1901082_1_1_1_1,00.html

[40] Why choose physics and chemistry? The influences on physics and chemistry subject choices of BME students ; http://www.iop.org/activity/policy/Publications/file_36117.pdf

[41] Total innovation; http://www.nesta.org.uk/total-innovation-report

[42] Innovation Index project; http://www.innovationindex.org.uk

[43] Demanding Innovation: Lead markets, public procurement and innovation; http://www.nesta.org.uk/demanding-innovation

consumer, and second, the general public as preferential consumers of innovative products and technologies. While perhaps beyond the remit of the current inquiry, it has been suggested that one of the reasons why the USA has reached such a strong position in terms of technological R&D and high-technology manufacturing is that it has a large and educated consumer market. This is an area which is often neglected in work to understand R&D policy.
In terms of the state as a consumer, policy challenges such as an ageing population and global warming will require significant public sector investment, and significant technological investment. Innovative public procurement strategies, tied in with programmes of targeted research could enable both the government to achieve its stated policy objectives and also allow UK science and technology to become world-leading in these areas. For such programmes to effectively work in promoting R&D and innovation, they require true cross-government support. It is essential that there is commitment from procurement leaders in all government departments, particularly the key purchasing departments such as the Ministry of Defence and the Department of Health. The Institute is of the view that to truly promote innovation and R&D in science-based small businesses a change in culture is required within government, understanding that while such strategies will involve increased risk-taking, the final products will often turn out to be superior and more cost-efficient in the long term than the results of 'over-specified' directed procurement. As a first step, the 2.5% of departmental R&D spending reserved for small businesses through the Small Business Research Initiative[44] (SBRI) should be raised to 10% and expanded across all government departments. It must be appreciated that the implementation of the SBRI has the potential to do so much more than merely develop innovative procurement solutions, and the success of the scheme should also be measured by its wider impact, including the benefits to the businesses involved and any intellectual property or jobs created in their local communities.

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?

The Technology Strategy Board:
As the key vehicle for implementing the government's innovation agenda, the Technology Strategy Board (TSB) has shown success in bringing together different strands of support around common themes. While programmes such as the KTPs and Knowledge Transfer Networks (KTNs) have been revitalised, it is the ability to bring a focus on specific areas of technology and industry which is the TSB's strength. The expertise and experience that the body now contains means that it should be in a strong position over the coming years to take a firmer leadership role in national and regional strategies for business support. Closely tied in with the TSB's activities has been the Business Support Simplification Programme[45], which has succeeded in reducing the number of distinct services by an order of magnitude. While it remains early days for this programme, the initial feedback from companies has been positive, and to maintain this, the temptation to start re-adding new and novel services outside the programme should be resisted, particularly over the next election cycle. One concern for the future role of the TSB is the tendency for the government to use it as a 'dumping ground' for policy objectives and to use its budget to fund projects that perhaps lie beyond its original remit. Both situations have the effect of watering down the primary role of the TSB and a clearer restatement of its mission may be needed in the coming years.

R&D Tax Credits:
The R&D Tax Credits were introduced in 2002[46] with the aims of stimulating domestic R&D and promoting inward R&D investment from overseas-based companies. While it could be argued that neither of these indicators has improved substantially since the introduction of the scheme, it should be remembered that the process is necessarily long-term and make take several more years to properly 'bed down' and that there are some signs of positive effects. A recent CBI survey has suggested that both the levels of satisfaction, and the cost savings delivered by the tax credits for participating companies has increased as the system has become progressively more integrated into the UK innovation landscape[47]. Perhaps most importantly, the CBI survey also suggests that R&D tax credits have influenced an increasing number of companies to either continue with or undertake additional R&D. For this to continue, companies should be given the confidence that the system will remain in place in the long-term. Any introduction of complementary schemes, such as preferential tax rates for work to exploit domestically

[44] Small Business Research Initiative; http://www.innovateuk.org/deliveringinnovation/smallbusinessresearchinitiative.ashx
[45] Business Support Simplification Programme; http://www.berr.gov.uk/whatwedo/enterprise/simplifyingbusinesssupport/page44802.html
[46] R&D tax credits; http://www.hmrc.gov.uk/randd
[47] Impact of the R&D tax credit: Adding value, reducing costs, investing for the future; http://www.cbi.org.uk/pdf/20090204-CBI-R&D-Tax-Credit-survey-report.pdf

produced intellectual property, should not come at the expense of the stability and sustainability (or the overall budget) of the R&D tax credit system.
Internationally, the scheme has had the effect of balancing similar schemes operated by other European countries such as France, and has pre-empted the possible introduction of a German scheme[38][48] and is a key part of the 'package' when promoting the UK as a venue of inward investment in R&D. The international comparisons should continue to be monitored, and the R&D credits system kept under review to remain internationally attractive to companies.

The Lambert Review:
The implementation of the recommendations of the Lambert Review coincided with an upturn in meaningful collaborations between industry and academia[49]. The breadth and flexibility of the resources available to both companies and universities, together with the level of promotion that has accompanied them have made the Review a significant success. Although, as described in response to question 13, this is perhaps less due to the template Lambert Agreements as much as the guidance and toolkits that are available to partners.

Regional Development Agencies:
The success that the Regional Development Agencies (RDAs) have achieved in the area of science and innovation appears to be very patchy. That is not to say that there haven't been areas of success, and some RDAs, such as the North West Development Agency, have made a strong contribution to their region. However, there is a great deal of anecdotal evidence that even in well-organised RDAs there is little adventure, vision or entrepreneurism. Together with this, there is a perception that the RDAs currently possess neither the skills nor the resources to complete their aims of reviewing SET and deciding the priorities in each region; something which will not give local businesses much confidence.
There are additional concerns about complexity in the levels of geographic duplication of support that result in businesses being able to apply for support from both regional and sub-regional bodies. This can result in confusion as to which is the appropriate body, especially related to sub-regional and city-based schemes that can alienate businesses outside these areas and also create conflicting targets. This division of resources at local levels also results in higher administrative costs, meaning a smaller pot of money is divided into sub-critical sums to be provided to businesses. Economies of scale in the area of business support can be best achieved by working on a regional level, rather than a sub-regional or local council level. Responsibility towards the UK strategy as a whole should reside with central government rather than each region charting its own course, with the themes of support set nationally, but delivered regionally. The Institute is of the view that the TSB should work to steer regional science and innovation programmes into areas which don't bring them into direct competition with each other, so preventing duplication and confusion being introduced into what is a national set of priorities, and instead build on the existing capabilities and strengths of the regions. This arrangement would have additional benefits for businesses located close to boundaries between regions that often experience significant problems when trying to accomplish 'cross-border' work.
Venture Capital Investment:
The recently announced government sponsored venture capital fund, the Innovation Investment Fund,[50] is a welcome development, even though the current commitment of £150 million may not be enough to make a significant difference. There is currently an acute shortage of funds accessible to smaller science-based businesses seeking investment, something that is likely to have serious and long-term repercussions in the UK economy. The effects of this drop-off are uniform across different sectors: science-based businesses start from a lower level of investment availability and so will be adversely affected. The longer term structural problems, which were identified by the Engineering Technology Board (ETB) in its *SET and the City* report[51], have meant that over the past few years, science-based businesses have struggled to obtain the long term, early stage investment they require. This is primarily due to low levels of engagement by larger venture capital funds and City Institutions, which is in stark contrast to the situation in the USA where investment from such funds drives the high technology sectors. The ETB highlighted issues relating to risk, and the lack of understanding of the prospects for science-based companies as key factors behind this lack of engagement and we agree with this assessment. To alleviate

[48] ZEW press release; http://www.zew.de/en/presse/presse.php?action=article_show&LFDNR=1114
[49] The Race to the Top: A Review of Government's Science and Innovation Policies ; http://www.hm-treasury.gov.uk/sainsbury_index.htm

[50] UK Innovation Investment Fund; http://www.bis.gov.uk/innovation/ukiif
[51] SET and the City: Financing Wealth Creation from Science, Engineering and Technology; http://www.etechb.co.uk/research/reports.cfm

this, and to tackle the immediate problems, any publicly-supported venture capital fund should have a greater understanding of science and maintain a strong focus on science-based businesses.

The ecology of research funding

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

While there is a role for both types of research in the UK, the balance of the system has swung too far towards targeted funding in recent years, and there appears to be a central lack of understanding that targeted research is dependent on curiosity-driven research having taken place, but not vice versa. Indeed, as Lord Krebs stated to the IUSS Committee: "*Applied research relies on the foundations that have been developed by basic research.*"[1] The success rates in EPSRC responsive mode panels in both physics and chemistry has been quite low over the past year or so. This is a real threat to the platform of internationally excellent research that a decade of improved science funding has generated, and that the RAE2008 measured.

In principle, the Institute is not opposed to targeted research initiatives that are closely linked to application, but they should not be at the expense of curiosity-driven research, as they are clearly not the same things. On this note we wholeheartedly agree with the view of the IUSS Committee which states that: "*Curiosity-driven research is a key component of a successful knowledge-economy. We strongly endorse the view that increased focus in applied and industrial follow-through should not be at the expense of blue-skies research, which is one of the UK's greatest strengths.*"[52] In addition, the amount of money that the UK is allocating to targeted programmes, often at the expense of curiosity-driven research, is not actually sufficient. For example, solving the energy and climate change issues of today and for future generations will require far more money than the entire Science Budget. Furthermore, the current targeted programmes suffer from a lack of scale both in terms of scientific breadth and timescale. It would be better to have fewer programmes of a larger scale so that good ideas developed over a greater period and a broader scientific range could be funded.

Therefore, the Institute proposes that in order to preserve funding for curiosity-driven research, targeted programmes of research (and their funding) could be removed from the remit of the research councils and placed within the 'lead' government department. For example, the Department for Transport could scope, drive and fund research into low-carbon cars, and the Department of Energy and Climate Change could take over the responsibility of the UK's fusion programme. The departmental budgets would then have the critical mass to tackle the major societal challenges and the scientific funding that remains with the research councils (which would be free from the political pressures that subvert funding patterns) could be driven on a peer review basis towards the goal of international excellence.

In such an arrangement, targeted research funding will still be accessible to academic research groups, but from a departmental base rather than through research councils. The new model may have further benefits in industrial collaborations, as the targeted programmes have tended to be at the more applied end of research, and provide strong market opportunities that can be tied in with public procurement strategies. This approach is not inconsistent with the Haldane Principle, and would allow the government to make a clear commitment to curiosity-driven research that will form the basis of future discoveries and technologies, while at the same time tackling today's major societal problems through targeted research. To facilitate this, as already stated a number times within our response, the number of STEM qualified people in government departments needs to increase markedly along with the schemes required to achieve this, and government departments and university STEM departments need to develop closer links, for example, through fixed-term secondments of academics, who will not only help run the targeted programmes but also maintain strong links to the curiosity-driven research landscape.

Of course, with any new proposal there are bound to be several pros and cons, and these will need to be aired and analysed thoroughly to avoid any unintended consequences (such as too much money being transferred from the research councils to government departments), but we are of the view that this proposal is worth considering as an option to alleviate the current tension within the research base.

16. 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?

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[52] Putting Science and Engineering at the Heart of Government Policy; http://www.publications.parliament.uk/pa/cm200809/cmselect/cmdius/168/16802.htm

Following on from our proposal in response to question 15, the following are some headline issues that we hope can be resolved in the future:
• A significant ring-fenced science and innovation budget that grows in real terms on a year-by-year basis that balances support between curiosity-driven and targeted research.
• Recognition of the special place of curiosity-driven research within the science base.
• Funders of research, whether it's the research councils, the EU, charities, government departments and/or the private sector, adequately cover the full economic costs of research.
• Stable research funding continues to be allocated on the basis of peer review, but the process needs to be more transparent, involve more international experts, and provide more constructive feedback to academics.
• The dual support system of support is balanced and there are sufficient funds in the QR pot for the funding councils to support research excellence wherever it is found.
• Greater coordination between the funding councils and the research councils, for example, to group and label research areas in the same way.
• A Science Research Infrastructure Fund (or equivalent) should be revived which is sufficiently funded and transparent to support the capital costs of university infrastructure.
• There is greater joined-up thinking and collaboration between the research councils in funding high-risk multidisciplinary research proposals and the costs of subscriptions to multidisciplinary international facilities and the maintenance and operation of national facilities.
• There is greater cohesion between the Large Facilities Capital Fund and the operational costs associated with running a facility so that the UK is in a strong position to bid to host major international facilities.
• It has been stated that the current system by which universities are engaged in research is unsustainable. If at some point, research is to be rationalised, i.e. the number of universities that undertake research is to be condensed with the possible introduction of independent research institutes, then it needs to be undertaken in an open, transparent and planned manner. In addition, it should be not be done without a robust model for teaching.

17. 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?

The role of this investment should be in meeting the policy objectives of the government's major societal challenges such as global warming and an ageing population. Much of this work is currently delegated to the research councils where, as targeted programmes, they occupy the same funding space as investment in curiosity-driven research. This creates the curious, and perhaps untenable position, where the quality of research in targeted programmes is assessed using the same metrics as curiosity-driven research.
As stated in response to question 15, to address the global challenges, and to better support the science base, the investment in the targeted programmes currently within the remit of the research councils could be relocated to the government departments that have the policy leads in the relevant areas. This would allow the world-class curiosity-driven research in the UK to flourish under its own terms and allow department-driven policies to be adequately funded without putting pressure on RCUK budgets and infrastructure.
In addition, bringing the targeted programmes together with the R&D currently operated by individual government departments brings the benefit of aligning the research priorities more closely with the national procurement strategy, so supporting innovative science-based businesses aiming to move from R&D to the marketplace. The Institute is of the view that the £175 billion procurement budget can be a driver of innovation. As discussed in response to question 13, innovative procurement strategies have the possibility of producing the most long-term cost-effective products for government while at the same time stimulating and supporting science-based businesses.
By connecting procurement with the targeted programmes, and driving targeted research funding, from university research to R&D in the private sectors and onto public procurement though a coherent and coordinated programme, government policies in areas such as low carbon transport and measures to combat global warming can promote science and innovation across the UK economy.

The Institute of Physics is a scientific charity devoted to increasing the practice, understanding and application of physics. It has a worldwide membership of over 36,000 and is a leading communicator of physics-related science to all audiences, from specialists through to government and the general public. Its publishing company, IOP Publishing, is a world leader in scientific publishing and the electronic dissemination of physics.

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Dr Jim McQuaid CB DSc FREng

10 September 2009

Royal Society Fruits of Curiosity Inquiry - Call for Evidence

A Novel Form of Science-Industry Interaction

Summary
This response concerns a particular model of science-industry interaction. The interaction is believed to be unique in its structure, going beyond existing frameworks and focusing on curiosity-driven research. The model enables different forms of value to be created for both sides and for the wider UK economy. It has been implemented successfully for some years in a partnership between a potash mining enterprise and a network of researchers on particle physics and nuclear astrophysics.

Background
Direct support for curiosity-driven, or 'pure', research seems to be rarely, if ever, offered by industry. Such research, by conventional definition, has no perceived connection, now or in the future, with industry's needs for business-relevant information or ideas. The stance of industry is quite understandable; support for curiosity-driven research is generally regarded as being in the province of government or charitable foundations. The Inquiry, in wishing to challenge the separation of this kind of research from 'applied' research, calls for a 'richer understanding' of how a research base 'creates value in many different ways'. The Call for Evidence quotes some examples of values so created. However, the examples relate to 'public goods' in the form of tangible outputs of the research or the research process. The purpose of this response is to demonstrate by example that the act of supporting curiosity-driven research can add value to the supporting business independent of value associated with the quoted 'public good' examples.

The Case
Cleveland Potash Limited operates a potash and rock salt mine at depths down to around 1100m under the North Sea at Boulby near Whitby. The depth of the mine ensures a low-background radiation environment particularly favourable for research in particle physics and nuclear astrophysics. These research topics do not confer any conceivable value on the mining operation. Yet for the past 20 years, CPL has provided free access to extensive underground space for a well-equipped laboratory for researching the above topics. The research scientists are able, at marginal cost, to use the essential supporting facilities of the mine, for example electricity supplies, ventilation, shaft transport for personnel and equipment, and so on.

The explanation for this benevolent act of supporting curiosity-driven research is provided in a statement issued by CPL. The statement is annexed and is self-explanatory. CPL has, in effect, identified a particular kind of value for their business from their interaction with pure science. The conventional separation of 'pure' and 'applied' research hardly applies. The research is 'pure' in the eyes of the scientists but for CPL it is 'applied' in the sense that the act of supporting it helps to fulfil a desirable business objective independently of the nature of the research.

Recommendation
The Inquiry may wish to consider whether the model of interaction practiced at Boulby should be promoted for wider adoption where similar circumstances apply.

Dr Jim McQuaid - Chairman, Deep Underground Laboratory Steering Group[53]

The place of scientific research at Boulby mine

CPL, the owner of Boulby mine, aims to be a successful mining operation exploiting the underground potash and salt deposits of Boulby.

[53] The members of the Group represent CPL, the scientific interests and The Crown Estate (owners of the mineral rights) under an independent chairman. The Group exists to provide strategic oversight of the operation of the Deep Underground Laboratory at Boulby mine.

CPL recognises that its success goes beyond achieving immediate commercial prosperity. Ensuring continued success in the longer term brings wider considerations into play. An obvious important factor is the influence it can exert on the social and economic environments in which it conducts its enterprise. The social environment, especially locally, benefits from the prosperity and a shared sense of pride in the mine's achievements. The economic environment, especially regionally and nationally, thrives on broadly-based innovation and scientific advance. The participation in scientific research at Boulby fits seamlessly into these two facets of an operating environment conducive to success.

The particular capabilities of the Boulby deep underground operations to support science was first capitalised on 20 years ago. This was in the context of being able to provide an environment with low background radiation, essential for fundamental research on detection of particles arriving on Earth from the cosmos. CPL cooperated in establishing an underground laboratory equipped and staffed for that purpose. Funding was provided from the UK Science Budget through the University of Sheffield and the Rutherford Appleton Laboratory. The research has since widened to other areas of particle physics and nuclear astrophysics. For the last six years CPL have also worked with Durham University on a range of scientific projects focussed upon gaining a better understanding of the processes that occur on coastal cliffs, and on aspects of monitoring and modelling large-scale rock deformation. Further applications of Boulby's capabilities for scientific research are in the pipeline. Strategic oversight of the research programme is provided by a Steering Group representative of the interests involved.

Although the scientific research at Boulby is remote from CPL's immediate commercial interests, the pursuit of fundamental research is seen by government as potentially contributing to the UK's future prosperity, directly by training the future generation of scientists and indirectly by encouraging young people to undertake careers in science and engineering.

The access to the Boulby mine is not provided on commercial terms and represents a substantial ex gratia contribution by CPL to funding the public good of scientific knowledge. The benefits to CPL are several fold. There is a direct benefit from the additionality to the viability of its mining enterprise due to the acknowledged symbiosis of having embedded within it a national asset which would otherwise be prohibitively expensive to construct and operate on an independent site. There are important indirect benefits too. The people employed at the mine are enthused by the presence of a world-leading research effort within their workplace. The interest of the local communities in the mine is fostered by an 'Outreach' programme in which the scientific research figures prominently. Internationally, the research places Boulby on the map as one of the very few facilities worldwide for underground research. In sum, the association with science is seen by CPL as a significant cachet to their operations. The Crown Estate, as the principal mineral owner at Boulby (for the area under the sea), is very supportive of the scientific research activity which in future is likely to expand into areas of the mine within its ownership.

Productive interaction between industry and science has long been sought by government. The partnership between CPL and science is unique in its altruism and provides a successful model of industry-science interaction.

Professor John Fox

Time, Training and Tribalism: Challenges to Effective Interdisciplinary Science

John Fox,
Professor of Engineering Science, University of Oxford and
Honorary Professor, Department of Oncology UCL and School of Informatics Edinburgh

This contribution to the *Fruits of Curiosity* discussion argues that despite frequent statements that interdisciplinary research is important for advances in many fields and for wealth generation the barriers to interdisciplinary working remain high. For scientists who are attracted to interdisciplinary and multidisciplinary projects there are major risks in terms of career development which push them towards safer, specialist career paths. There are also damaging consequences for British science and society in terms of opportunities missed for discovering novel research directions, validation of theory outside the lab, and the frequently observed weakness of the UK in translating the results of its world class research into practical applications and commercial opportunities.

Biographical note. *I trained as a laboratory scientist with a mixture of theoretical and applied interests. Since then I have found myself in departments of computer science, medical physics, medicine, psychology (theoretical and applied) and social science and I am now in the Engineering Science Department at Oxford University. Following postdoctoral positions in the US and UK an unusual opportunity arose when Walter Bodmer, then Research Director at ICRF (now Cancer Research UK), recruited me to help develop a biomedical informatics programme at ICRF in 1981 and to set up a lab working on AI and its biomedical applications. This led on to a long term CRUK career with support for a multidisciplinary research team with relatively generous core funding. Funding for the programme was maintained by Paul Nurse and later CRUK directors until Mike Brady invited me to Oxford to set up an interdisciplinary collaboration in cognitive science and systems engineering where I am now trying to apply our concepts, technologies and interdisciplinary approaches more widely (www.cossac.org).*

Sustained and often generous funding for research programmes that bridge the life sciences and practical clinical medicine is relatively common. Indeed it is almost the norm in biomedicine where large problems demand large teams. But such funding opportunities are rare in the other fields in which I have found myself working. Sustained funding of course allows the lucky scientist to take a long view, take risks, and combine curiosity driven enthusiasms with projects aimed at translating results into uses. My colleagues and I at CRUK were able to make contributions in computer science and cognitive science, develop a number of practical technologies to address medical problems which were made possible by advances in basic science, and trial a range of applications in the clinic. The work led to two commercial spinouts and another in development.

As remarked earlier the importance of interdisciplinary and multidisciplinary working is widely recognized and some of the basic obstacles are well known. Researchers must acquire knowledge and experience in several fields; this is perceived as a brake on their careers and can make it difficult to establish a reputation in any specific area. Interdisciplinary projects are also difficult: different specialist communities have different languages and concepts and often have different notions of what the problem is. It must also be said that a little tribalism sometimes creeps in. As the late Roger Needham FRS once said "every researcher sees his own research as paradigmatic of how research is done: this gives rise to every kind of confusion". However, although the issues may be known the strategies for overcoming it are rarely put in place in an effective and sustainable form.

A virtuous circle of theory-to-application-to-improved-theory, is in my experience a hugely productive research strategy but it is not possible in many institutions in the UK as the most common funding structures don't support it. I see many talented university colleagues struggling for modest research funding, usually of 3 or at best 5 years, which is inevitably focused on narrow questions and whose output is largely limited to peer-reviewed publications. Shortage of time and resources makes it impossible for most scientists to seriously consider a cross-disciplinary career, even less a translational project, though I am sure many have the interest and ability.

What do we need to do? If we are to stimulate the creative juices and simultaneously improve the pull-through of basic research into practice we need a support model that explicitly embeds high quality science in a translational framework that enables effective interdisciplinary and multidisciplinary working where this is appropriate. A Structured Interdisciplinary Research Programme (SIRP) would be likely to have a number of distinctive features.

1. A key objective is to make long-term interdisciplinary working attractive to talented multi-skilled scientists, mitigating some of the risks of making this career choice. A SIRP should support a coherent interdisciplinary career path that is realistic about timetables and training needs - and rewards. Short "discipline hopping" awards do not address this.

2. The productive lifecycle of an interdisciplinary programme is necessarily longer than a comparable specialist programme, particularly if the funder wants to see the research it supports translated to practical applications (as seems so often to be the case these days). The default funding period for a SIRP should therefore acknowledge this; a 7 year programme with scheduled reviews against clear objectives should be the norm for this kind of programme rather than 3 or 5 years with a "possibility of renewal". The Interdisciplinary Research Collaborations supported by some research councils acknowledge this but do not put career and management structures in place to make the most of the longer term funding; the subsequent points address this observation.

3. The best specialists do not often make the best interdisciplinary leaders and SIRP awards should be explicitly aimed at recruiting world class "all-rounders" in the PI role. Measures of success consequently need to be developed for identifying interdisciplinary talent and rewarding success that are more appropriate and multidimensional than the traditional measures of success in specialist science, such as citation rates. In commenting on a draft of this paper in light of EU (ERC) experience and approaches Professor Nowotny identified the problem of developing and implementing appropriate and effective peer review procedures for multidisciplinary proposals as a key challenge.

4. Aspiring interdisciplinary scientists need time to gain interdisciplinary skills and experience, and training opportunities. SIRPs may benefit from allowing for a slow start-up phase, rather than the conventional big-bang funding structure, allowing induction and training of staff to take place progressively. They should also make provision for break-out periods for further training, which enhance rather than damage career prospects. SIRPs should be designed to accommodate flexible spending profiles as interdisciplinary understanding, skills and relationships are established by the team.

5. Management of interdisciplinary programmes can be *extremely* difficult. This is particularly the case where team members are located in different departments or institutions with no single line manager. It is also hard for even the most talented scientist to be the natural leader in all the areas covered by a project. Mechanisms need to be put in place to help PIs manage interdisciplinary teams, including formal management structures and employment contracts which balance opportunities for blue-skies and curiosity-driven research with responsibilities for interdisciplinary working and translational projects.

6. SIRPs are likely to need significant resources which are earmarked to support collaborations and build relationships across departments and institutions. For example they may include funds for exploratory interdisciplinary meetings, initiating pilot projects (which may well have a high failure rate), seeking specialist advice and assistance etc. This extra flexibility is needed because of the relatively long life-cycle of a SIRP and because needs and opportunities are more difficult to anticipate in an interdisciplinary setting.

7. SIRP proposals should include an explicit decommissioning phase when the most creative parts of the project are likely to have been finished and the emphasis moves to exploitation. The big bang start-up is currently mirrored by a sudden collapse of funding at the end of a programme, which leads to no end of issues. The PI and the funding bodies should have a clear end game whose goals are, for example, to maximize the impact of the project on the shortest reasonable timescale and to assist staff in moving on to new roles, which may now be relatively late in their careers.

Thanks to Mike Brady, Paul Nurse and Helga Nowotny for helpful comments on earlier drafts.

John Innes Centre

Royal Society - The Fruits of Curiosity

Response from the John Innes Centre, Norwich Research Park, Norwich NR4 7UH.

The John Innes Centre is currently celebrating its centenary and has a proud tradition not only of research but also of training science's next generation, starting with William Bateson FRS, the founding Director of JIHI, who pioneered the science of genetics in Britain and coined the word "genetics".

Our initial responses to the enquiry's questions are laid out below.
Our staff, a number of whom are Fellows of the Royal Society, would be happy to assist with this project further if the Advisory Group would find this helpful.

Friday, September 11, 2009

The long-term direction of policy for science

1. What role should curiosity-driven research play in the UK science base in the next 15-25 years?
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?
3. 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?
4. How should science be governed to maximise benefits to society while acknowledging public questions, uncertainties and concerns?
5. How should we assess the long-term social and cultural impacts of scientific research?

Curiosity-driven research must be allowed to continue to thrive alongside strategic work, to avoid the danger of missing out on the unexpected. Funding bodies should 'ring-fence' a proportion of their budgets for 'blue-skies' work. It is difficult to predict what will be "useful" in the future. We need to avoid being too "top down" and sucked into "fashionable" new areas at the cost of existing, excellent fundamental science. There are many examples of curiosity driven science that have led to unexpected outcomes with real application through innovation and enterprise. The 'trick' is to recognise the potential for application and foster that and to provide cultural frameworks that foster and reward such endeavour amongst scientists. Examples at the JIC would include the discovery of novel antimicrobial therapies (e.g. control of gene action and synthesis of novel antibiotics – both now in spin out companies - through fundamental study of *Streptomyces*) and recognition that the genetic control of dwarfing in *Arabidopsis* is part of a fundamental mechanism to control plant growth overall, with direct parallels into crop species.

We should maintain a mixed economy of large- and small-scale grants in order to accommodate different modes of carrying out research. Although syndicates are becoming the 'norm', one of the UK's strengths in the past has been in bright, inventive individuals who are less likely to conform, or desire, to be part of such groups. It would be a pity if this pool of talent was lost.

To facilitate the necessary interactions between individual scientists across national boundaries that foster the development of new scientific directions and collaborations worldwide there are a number of sources of funding for initial interactions/meetings, but then little means of subsequent funding of research. This is notable with interactions between the UK and North America which causes frustration amongst the scientific community. We need to establish robust, international (esp. non-EU) funding schemes (for example with the USA and China) that provide real money (salaries, consumables.) to nourish 'natural' collaborations.

The UK needs to do science in a global context – not only in terms of how it does science (of top quality but also cost effectiveness) but also in terms of what the science is applied to. The "fortress UK" mentality is outdated. We should embrace the concept of partnering with more applied national research organisations such as Embrapa.

The UK can and should become more engaged with developing agendas in EU science, and in helping UK academics to get their science onto the EU agenda. Benign neglect and leaving this to talented individuals who are funded by their research institutions is risky in a tight financial climate.

The UK has made great changes in its governance of science in recent years, with citizen scrutiny the norm. This needs to be carefully balanced through a process of informed discussion. What must remain in place is that the basis of awarding funding to scientists must continue through the peer-review process to ensure that funding bodies support only the highest quality science. A substantial percentage of the population remain disengaged with leading-edge science and this needs to be addressed with projects which will fire enthusiasm for the importance and pervasiveness of science in every-day life; issue-driven engagement often comes from a the perspective of science as opposed to the citizen.

Noting that peer-review is essential it will be important that funding bodies are able, through this robust process, to ensure that plant science which remains leading edge but may be a progression from model to crop species can still be competitively funded and supported. This is essential if we are to succeed in innovation and application.

Investing in tomorrow's talent in schools, universities and in the FE sector

6. 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?
7. What are the future challenges for STEM education at primary, secondary and tertiary levels? How should these challenges be addressed?
8. 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)?

In education we are particularly concerned about the increasing focus on high schools and reduced emphasis on primary schools. It is obviously important to get high school children excited about and interested in science; but not at the expense of science education in primary schools. It is essential that children are fired up about science at as young an age as possible. By the time they leave primary school they already have fixed ideas that will ramify into high schools.

Although many scientists and organisations have programmes to try to capture the interest of young people, our view is that many of the approaches are in isolation and lack rigorous evidence of efficacy. With financial support from the BBSRC, we are currently examining our programmes for 'Inspiring Young Scientists', to establish a more focused strategy for the work that we undertake in this area.

We need to establish mechanisms for increasing the status and attractiveness of the teaching professions in STEM. But it is not essential for graduates to move immediately into teaching. Indeed, a number of John Innes Centre alumni have moved from research to teaching and our evidence is that the training they have received at the bench helps make them inspirational in the classroom. Initiatives such the Teacher-Scientist Network, based at the John Innes Centre could benefit a wider group of teachers were there funding to resource, for example, e-learning initiatives.

Building and sustaining research careers

9. 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?
10. What sorts of incentives can we develop to keep talented students and postgraduates in science?
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?

We need to ensure that strong research scientists in Universities are supported and protected. But Universities should think more strategically and focus on research excellence in fewer areas, rather than try to a bit of most things.

The Norwich Research Park is a case in point – the recognition by JIC's former Director Chris Lamb FRS of the potential of Norwich, and his drive to develop it's Science and Innovation Vision, has resulted in a powerhouse of research which is driving forward on specific pillars of excellence.

We need to ensure that science career structures (B.Sc., Ph.D., PDRA & beyond) are well-defined and well-resourced as a recognised continuum to attract the most talented individuals. This should not be at the expense of ensuring that moving from an active science bench career to another profession is encouraged and fostered through this process. The science career pyramid narrows acutely and those entering the process must be able to recognise this and set realistic career goals against that framework. Increasing the number of scientifically-literate staff in non-science professions, for example in banking/venture capital has surely to be an attractive proposition in the UK-context.

Movement between academia and industry should be further encouraged/resourced and regarded as the 'norm' rather than as an exception. Sabbaticals should be actively encouraged, and financially incentivised.

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

All academic institutions should have innovation capabilities, particularly individuals who 'seek out' academics and discuss and take forward potential new innovations. Although there has been a change in outlook on the part of many academics, more needs to be done and we need incentivisation such as the clearly laid out and unencumbered "Rewards to Inventors" schemes.

There need to be robust, hard-wired mechanisms for collaboration between industry and academia. The LINK schemes that we have been involved in have generally been very good, and provided real opportunities for collaborative work with industry, and an easy mechanism for commercialisation, but they seem to have fallen out of favour. In particular, IP arrangements need to be clear and attractive to industry. This seems currently to be a great missed opportunity, e.g. in antibacterial drug discovery.

There are ways to achieve public funding for public-public research collaborations, but these routes are mainly for fundamental research. We believe a parallel should be available for "public-public" (national and international) collaborations on applied/development R&D topics. To achieve impact from public innovations, the funding balance needs to shift somewhat more towards taking such innovations further forward (flexibly, intelligently and not necessarily by the organisations that created them in the first place) within the public sector before expecting commercial uptake. Collaborative research (and even technology development) projects with non-UK (not just UK) companies should be encouraged/supported.

The John Innes Centre part owns a technology innovation company, PBL, which is a successful model working in this field because it sits on the JIC campus and is able to interact with leading scientists at early stages in the scientific process ensuring that innovation and the necessary protection can be developed collaboratively.

Small Business Innovation Research (SBIR) grants in the US are extremely useful in enabling academics to launch companies and get them up and running. We have something similar here in the UK – SBRI (Small Business Research Initiative) - but our view is that this is more constrained, and less effective from an academic perspective.

The ecology of research funding

15. How do we maintain an appropriate funding balance between curiosity-led, response-mode research,and more targeted or programmatic funding?
16. 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?
17. 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?

We need to look carefully at funding gaps between current grant-awarding bodies and ensure that there are joint funding schemes (e.g. MRC/BBSRC) that accommodate exciting and ground-breaking work at the interfaces. Generally our experience of departmental spending is that it does not encourage curiosity-driven research, although some of our experiences with DEFRA LINK have been very positive.

Dr Kuang-Hsu Chiang

In response to "Fruits of Curiosity" - call for evidence:
Blue-Skies Research Goes Underground? Time to Ask Some Serious Questions

Dr Kuang-Hsu CHIANG
University of Edinburgh

September 2009

It is almost an open secret among scientists nowadays that if one would like to do blue-skies research, one has to do it in a concealed way – for example, using the funding left over from other projects or secretly developing the blue-skies research alongside other applied projects. The reason is very simple: there is neither enough financial support nor policy recognition for such research.

Behind the above obvious reason, there exists the ignorance of the value of such research especially among policy makers and the government. The first set of important questions need to be asked is: what makes blue-skies research distinct from other types of research? And why is it valuable? This article is based on eight preliminary interviews with prominent scientists in Biosciences, Physics and Chemistry who are or have been doing blue-skies research across the UK, France and Sweden.

The value of blue-skies research

Scientific research can generally be categorised into two groups. The first one is evolutionary or incremental where most research belongs. The other group, called "blue-skies research" or transformative research, is rare but has the potential to revolutionise existing fields.

Blue-skies research is characteristic of its radical, surprising, momental and grounded nature. It deriving from laboratory grounds can lead to significant breakthrough, radical transformation of the field, or even the creation of a new knowledge paradigm. Therefore such research has this bottom-up or democratic flavour and cannot be planned in advance. The above qualities make such research different from basic and applied research, which focuses on incremental progress of knowledge.

The value of such research lies in its adventurous and pioneering nature which lays down the foundation and opens the door for all the other types of research. As Professor Jean-Marie Lehn (French Nobel Prize Laureate in Chemistry) put it: "totally free, 'blue-skies' research as the requirement for fundamental advances" gives birth to both basic and applied research as well as all the other kinds of research.

From the literature, blue-skies research is seen to be linked to radical creativity. It was found that different organisational settings facilitate different types of academic creativity and research. Ekvall (1997) found that radical creativity is likely to be stimulated by "looser structure, more freedom, higher risk-inclination, and debating, dynamic and playful atmosphere" (p.200). On the other hand, strict, rational, structured environment facilitates adaptive creativity. Marginson (2008) and Beller (1997) reasoned that radical creativity is related to high academic self-determination and academic freedom.

Current policy environment

This is why current scientific policy featured by its top-down approach by being risk averse makes blue-skies research suffer. The most recent examples are: the advocation made by the Science Minister Lord Drayson for the economic benefits of research (Times Higher, 29 Jan, 2009); the demand from research councils for demonstrable impact in any grant application. Top-down and structured approach may be suitable for some types of research which have a more applied or industrial nature. It is however not incongruence with the unexpectedness and the grounded nature of blue-skies research.

Notwithstanding, blue-skies research has not always been treated in this way. In the 1960s and 1970s, the scientific climate was completely different, as one of the senior Chemistry professors at Oxford pointed out. In those days, the government adopted a "laissez-faire" approach. Scientists were left alone to follow whatever direction their curiosity led them. Blue-skies research flourished during this time. The laissez-faire approach which is inclined to be in congruence with a bottom-up nature and in accordance

with unexpectedness and openness, created a suitable political and scientific climate for such research. As a result, this generated significant breakthroughs in science. It not only established the leading status of British scientists in the world but also resulted in remarkable innovations and applications in improving human lives, from which we are still benefiting today.

The policy makers and the government nowadays may argue that for the sake of national and societal interests, a more top-down approach is needed to make research funding more accountable. It however overlooks the factor that different managerial settings facilitate different types of academic creativity and research. Some scientific research already revealed that radical creativity, which is essential for blue-skies research, is likely to be stimulated by the kind of climate which has looser structure, takes higher risk, gives more freedom and is characteristic of vigorous and frisky ambience. Strict, rational and structured environment only facilitates adaptive creativity.

Time for reflection

If this continues to be the case, then the questions that need to be considered are: how long will it last before we use up the intellectual fruits that we inherited from the blue-skies research carried out by the previous generation of scientists? How much time do we have before blue-skies thinking becomes vanished from British universities? How soon will it take before scientists working in other higher education systems take our place in the scientific world? Eventually what does this mean to the training of our next generation of scientists?

It is also worth asking: is this what we are thinking to cultivate through current Higher Education funding and assessment regime? What kind of scientific visions do we have? what kind of research the UK is thinking to cultivate? Is it aiming for research with immediate results, of incremental advancement, or the kind of research which will lead to radical transformation of scientific fields as well as human lives? By creating an environment which favours only certain type of research, does current funding and assessment regime really work for the best public interest that it sets out to defend?

For the advancement of human society as well as science, we cannot depend on just one type of research, no matter how excellent that is. Perhaps it is time for policy makers, government and scientific communities to think about some of the above questions before it gets too late.

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Dr Laurence Cox

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?

A: There is an issue with pay for those pursuing a research career. I don't think that it is possible to match the pay rates that those in the financial services industry receive, but it is entirely reasonable to match the pay rates to managers in the same organisation. I think that it was Bell Labs in the USA in the days before AT&T were broken up that had a policy of paying their best scientists and engineers as highly as their best managers, so that there was never a financial incentive to stop research and to move into management just to get to the next rung on the ladder. Although companies pay lip-service to this principle here, I have never seen it occur in practice.

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

A: An important factor is the level of student debt. One incentive could be to pay off a proportion of a student's debt for spending time on postgraduate studies in science and engineering.

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?

A: The standard career-track model does need to be re-evaluated. At present, movement of skilled individuals is largely from academia to industry and business, and this is because of academia's obsession with published peer-reviewed papers as a measure of merit. This could have the effect of deterring academics from trying out business (although I think that this is less of a problem since Universities in general have set up their own IP units to commercialise inventions made by their staff) and it certainly makes it difficult for anyone who has been out of academia for more than a few years to return. The presence on the teaching staff of people who have had experience in business will also help to encourage undergraduates to appreciate that research outside academia can also be challenging.

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?

A: MoD has been running a programme called Ploughshare for several years, precisely to enable IP generated in Ministry research establishments to be applied by commercial industry. MoD scientists receive recompense for their ideas that are taken up. Knowledge and expertise also flows the other way through the DTCs.

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

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?
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?

A: The principal issue that I am concerned about is the effect of shocks on the system. Examples include the formation of STFC and changes in exchange rates on subscriptions for international facilities. It is not reasonable to expect a research funding body to cope with a sudden change that is outside their control. I think that it is part of Government's responsibility to cover the effect of exchange rate fluctuations, by guaranteeing a set level of subscription at a specific exchange rate (or by specifying part of the funding body's grant in the appropriate currencies). If the funding body wants to increase (or decrease) its subscription beyond the set level, that is its decision.

The second issue is that funding needs to be predictable. If a five-year forward budget for the total amount that a funding body receives is set and updated every two years, then everyone knows how much new money is available each year and can plan with confidence for the future. Government-imposed changes on funding would have to be limited so that new money could not be wiped out by a budget cut.

Another concern I have, as an outsider, about the present funding system is that people whose proposals are not funded are being barred from bidding again for the same work, rather than being encouraged to improve the quality of their proposals and resubmit. This seems to be being done for administrative expediency to reduce the number of proposals, rather than to sift out the proposals that would never be funded.

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?

A: I think that defence research needs to be looked at as part of the science budget. In the past, defence research was treated entirely separately from non-defence research, most of it carried out within MoD establishments, with no emphasis on the possible paybacks outside the defence field. With the separation of DERA into QinetiQ (private) and Dstl (government), the setting up of a separate Research Acquisition Organisation (RAO) and the involvement of commercial companies in the "Towers of Excellence", the funding of defence research has become more like the funding of non-defence research.

Defence research funding fits uncomfortably within the MoD's budget, which primarily funds two large costs: the running costs for the armed forces and the procurement of defence equipment. Defence research funding is small besides these two and is always in danger of being squeezed. I think that there is a good argument for taking defence research funding out of the MoD budget and putting it directly under the control of the RAO. I think that the RAO would also benefit from leaning the lessons that have been learnt by the research councils in budgeting.

Dr L J Cox

Steve Jewson

My submission relates to 'The long-term direction of policy for science' and 'Science, innovation and wealth creation'.

In particular, it relates to government funded research in the areas of weather, climate and climate change.

My view is that the government strategy in these areas over the last 14 years has been a complete failure, when judged in terms of whether it has produced anything useful for industry, or spurred industrial innovation in this country. In fact, government policy has been stifling growth and innovation.

In brief, the government strategy has been to make the Met Office into a trading fund, that is forced to charge for its services and keep its data and products proprietary.

Because of the prohibitive fees charged by the Met Office, most of UK industry simply has no access to the products of weather and climate research produced in the UK, and has to obtain such products from the US. Also, companies that perform R&D in this area in the UK are effectively prevented from collaborating with the Met Office (because it is a competitor) and are forced to collaborate with equivalent US institutions instead.

For instance:
-UK industry relies almost entirely on weather data (including weather data for the UK) provided by US government agencies
-UK industry relies almost entirely on atmospheric models, ocean models and climate models developed by US government agencies
-UK industry relies almost entirely on reanalysis data sets produced in the US.

There are large, and growing, industrial opportunities related to the provision of information about weather, climate and climate change. But innovation in the UK is greatly stifled because it is so hard to get the raw materials (the basic data, and the basic models) that are needed to capitalise on these opportunities. As a result, this rapidly growing sector is becoming more and more dominated by US companies, where the raw materials are provided by government free of charge.

I'd propose that the UK needs to completely revamp its policies related to government funded research in weather, climate and climate change. This could be done in many ways, but the key ingredients would be
a) a policy of free access to all products developed by government agencies.
b) a policy that government agencies should not compete with the private sector

Best regards,

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LGC
(Laboratory of Government Chemists)

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

Response from LGC

We welcome this opportunity to enter into a new round of reflection on the role of science in, and for, a better future.

The long-term direction of policy for science

1. What role should curiosity-driven research play in the UK science base in the next 15-25 years?
Curiosity-driven research will always be a national asset because new discoveries might be applicable to current and future issues and industrial developments. Fundamental research such as establishing the structure and function of atoms, molecules, nanoscale structures and cells continues to pay dividends to society and underpin new advances leading to further benefits. To bolster the case for curiosity-driven research, we must be quicker to recognise the potential applications as they emerge. However, a balance needs to be reached between these probable latent benefits and longer-term research targeted on areas combining challenge and societal need. Such research thrives in the context of application-driven grand challenges - current examples being food security, national security and providing a global environment fit for our children.

Curiosity-driven research will be increasingly multidisciplinary because many of today's strategic challenges, such as crime reduction, the low carbon economy and wider sustainability, and counter-terrorism, spark off burning questions (for example, 'What tools do we need to enable proportionate, risk-responsive threat reduction?') which can only be addressed effectively through close collaboration between the scientific professions.

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?
The last decade has been a period of intensive policy development, with variable results, as might be expected where genuinely novel ideas and approaches have emerged.

In some areas, policy has led to improved UK assets - the Diamond synchrotron being one such success story. However, technology transfer remains weak. We still face an uphill struggle to convert the UK lead in publications and citations into wealth creation. No doubt the impact of the Technology Strategy Board (TSB) will become apparent over time. The recent creation of the National Measurement Office (NMO)54 establishes a resource that academia, Government and industry can draw on to support wide-ranging scientific requirements and quantify critical outputs. NMO should help ensure that the roles of enablers such as analytics, along with the benefits of drivers from technical standards and regulation, are more clearly understood and incorporated into innovation route maps.

We are aware that the innovation support framework has something of a blind spot for outstanding ventures that may require funding in the £250k–£1m bracket to live up to their potential. Perhaps it would be appropriate to develop a mechanism linking such opportunities with UK strategic priorities or grand challenges.

Policies favouring innovation and knowledge transfer have helped to strengthen collaborative, interdisciplinary working. For example, a typical collaboration between biochemists, analytical technology providers and research chemists might now aim to resolve underlying questions about mechanisms of nutrition or toxicity whilst developing novel marketable scientific products and services.

The ongoing development of European and international policy creates new contexts for the delivery of scientific programmes. That international co-operation provides new insights and the benefits is

[54] http://www.nmo.bis.gov.uk/

evidenced by universities now having overseas campuses to integrate better with the global research community. Insofar as scientific knowledge, once established with confidence, is universally valid, high-level co-ordination (such as that relating to measurement standards provided through the European Metrology Research Programme – EMRP – and Bureau International des Poids et Mesures – BIPM initiatives) can contribute to efficiency and ensure that replication within studies is of a rational rather than ad hoc nature. Provided that such efficiencies are not lost, the development of devolved and regional policies can also harness local strengths to benefit UK science and innovation.

3. 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?
Investment in science by emerging economies is clearly a threat to our relative ranking, and therefore to the attractiveness of the UK as a place to nurture skilled scientists and undertake world-class science. We are unlikely to match the larger countries in terms of absolute expenditure, and therefore need to make the most of what we are able to invest. This means attracting and retaining the best people, concentrating on the right areas where the UK has market 'edge', and having the most supportive infrastructure for underpinning and application-based science - in fact, an approach that sets the nation apart may be as important as efficiency. The UK has retained strengths in pharma and biotech sectors, and has developed leadership in fruits of curiosity research such as regenerative medicine (stem cells). We believe that areas of existing industrial strength, as well as those with a promising innovation pipeline, offer the best prospects for UK science provided that there is a global appetite for their progress.

We need also to co-operate with those countries that are investing so that we can share understanding and benefit. We can promote such knowledge exchange by fostering a co-operative spirit and by means consistent with the national interests of all the global players. The National Measurement System (NMS) is a robust vehicle for knowledge exchange as it develops techniques and infrastructural tools (such as laboratory reference materials, technical guidance and international performance comparison schemes) to create a level playing field for trade and to underpin global priorities such as healthcare, security and sustainability.

4. How should science be governed to maximise benefits to society while acknowledging public questions, uncertainties and concerns?
The key has to be the greater use of expertly-informed governance engaging with a society that has access both to the facts and the means to interpret them objectively. In particular, scientists need to explain 'known unknowns' clearly so that stakeholders can form evidence-based opinions - for example, concerning levels of exposure to hazardous anthropogenic substances through the environment. In the governance of GM innovation, lessons are still being learnt about the need for balanced communication of benefits and risks, alongside recognition of ethical considerations that cannot be resolved by science alone.

5. How should we assess the long-term social and cultural impacts of scientific research?
Meeting grand challenges, including sustainable living, food security and ageing, is a precondition for social and cultural wellbeing. These challenges thus present opportunities for scientists to demonstrate the wider impact of their research. At the programme level, best practice is to evaluate all forms of impact, including short-term and long-term economic (Lambert model), social and cultural (quality of life), science innovation, and knowledge transfer. Social and cultural requirements are likely to change as underlying expectations and pressures evolve – life expectancy being a case in point. Alongside such standard of living indices, the fortunes of innovative SMEs and technology companies are quantifiable, but indirect measures of impact.

6-8. Investing in tomorrow's talent in schools, universities and in the FE sector
Our main perspective on this topic is as an employer. We believe that a flexible, curiosity-driven curriculum is essential to improve the problem-solving skills presented to the employment market by school leavers and postgraduates. Experience in the design and interpretation of experiments is at least as important to us as the ability to source and present established facts (although a judicious and critical approach to the use of online resources is also essential).

The education system could do more to differentiate applicants according to their skills and aptitudes. Despite the apparent improvement in school exam grades, we see no noticeable improvement in the

literacy or numeracy skills of those entering employment, and indeed at degree level the reduction in practical activity associated with science courses means that we are undertaking more internal training of new staff than was required a decade ago. Expectations increasingly outweigh innate ability. The 'power' appears to have shifted from the educator to the educated with the provision of an environment where all have to succeed. A proper education philosophy is required. Accessible vocational training for those in employment has been identified as important, and we support continued initiatives in this area.

Action along these lines could also help to ensure that the next generation of teachers and tutors are adequately qualified and specialised. For both students and teachers, role models are important, and the Royal Society of Chemistry's activity in support of chemistry education is a leading light in advancing STEM[55] and women in science and education (WISE).

Building and sustaining research careers

9. 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?

Particularly during and in the aftermath of the economic crisis, job security is likely to be even more highly valued than in the recent past – as an employer, we are seeing more people that may have chosen careers in finance (in the City) 'returning' to their roots in scientific education. Setting aside questions of tenure and the grant-led culture, a special kind of security derives from the intrinsic, exploitable value of scientific knowledge, which holds out the prospect of long-term employability. Each scientist develops unique expertise and has skills and perspectives that are marketable throughout their career. The variety of opportunity for personal development and fulfilment, whether in academia, industry or beyond, is an added benefit. Moreover, the heartfelt recognition, in some quarters of government and society, that innovation is the key to a sustainable modern economy tends to suggest that science will be valued more highly as the links to societal wealth and wellbeing become clearer.

Given this impressive package of potential rewards, specific action is needed to get the message across to young people. Mainstream television has recently made something of a fresh start by presenting aspects of science in a way that it not only entertaining, but informative and realistic. Such programming could go further in prompting and considering the question 'How can I become part of the picture?'

Aspiring academics need systems to support rather than hinder them in doing their job. For example:

- Low grant award rates mean that vast time is spent in preparing applications to sustain valuable research - often on repetitive and unproductive tasks. A smoother signalling system might help
- The culture of mass education to university degree level is tending to increase the teaching time demanded per capita from academics. The UK needs to be realistic about the relative benefits of time spent teaching and on research
- Unique expertise needs to be sustained and nurtured, particularly where flexible careers are concerned (e.g. female returners to work after childbirth).

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

Novel mechanisms to offset university expenses, or perhaps utilise stage-gate models of repayments, could prove increasingly important in securing and supporting commitment to careers in science.

In addition, scientists at all levels need inspiring and successful role models, or at least a visionary framework for the development of rewarding roles and responsibilities matched by recognition, value and reward. Financial reward is a central concern - in some cases, just to the extent of making ends meet. Profit-sharing from innovation can be a highly effective retainer, particularly where scientists can track a venture's progress, feel part of it, and contribute to common goals in the context of exploring their own interests. LGC is an excellent case study in the benefits of profit sharing (we can expand on this observation if you wish).

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?

[55] http://www.rsc.org/Education/AboutUs/

The key is preparation of individuals for work, wherever and at whatever level this is, and work experience is of particular benefit. Flexibility acquired over the course of formal education and early career development is undoubtedly seen as a potential advantage in terms of differentiation over others. Many MSc courses provide real opportunity to experience both academic and industrial cultures, and businesses are also likely to be receptive to 'thick sandwich' undergraduate placements akin to those offered in the 1980s. From an employer's perspective, given the number of 'similar' students emerging from the current education system, MScs and long placements provide a sound basis for recruiting decisions. At postgraduate level, the Technology Strategy Board's Knowledge Transfer Partnerships (KTPs) are proving to be an excellent way forward.

Intervention may be required to encourage industrialists, career breakers (e.g. after maternity leave) and movers to return to education and work, and would be justified according to the relevant experience that they can bring.

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?

Industry is now generally aware of the need to innovate in order to compete - year by year, global competition intensifies and cements the message. The question perceptively focuses on how we move on to address this need. Knowledge Transfer Networks[56] can certainly be helpful, particularly if they are sustained long enough to become familiar and trusted resources for the communities served; and the Knowledge Transfer Partnership[57] model holds promise. Given that the UK has achieved some measure of success in establishing science-led collaborations between the public and private sectors, translational R&D is becoming the key to delivering outcomes of real and lasting value.

All the key organisations with enabling roles need to play their part in the exchange of knowledge and expertise. Knowledge exchange is hard-wired into the NMS, pervading the portfolio of UK measurement programmes. In fact, there is a dedicated Measurement for Innovators (MFI) programme[58], combining consultancy, staff exchanges and collaborative opportunities, which provides a powerful model for knowledge exchange geared to the needs of the private sector, and particularly SMEs. We work with the innovation community to facilitate market entry and expansion, as well as applying science to ease the burden of regulatory compliance (for example, as home to the UK Government Chemist[59]).

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

The Society could perhaps help directly by building on past experience of stakeholder pairing schemes; this would mean focusing resource on academic-SME partnerships and innovator-industrialist ventures.

The national measurement laboratories are already applying a range of effective tools to support private sector R&D - and particularly innovative SMEs - but certainly seek to scale up the impact. For example, we offer:

- World-class laboratory facilities
- Translational R&D in areas prioritised by stakeholders
- Methods of measurement adapted and validated to support important applications, backed up by user-friendly reference materials to aid comparison of the results
- Testing schemes that enable a company's scientific performance to be compared objectively with peers, without prejudice to IP
- Expert-led guidance on best practice for making the measurements needed to underpin progress in emerging fields.

Scientists working in the private sector need to be ready to contribute actively to company strategy, and work to ensure that their ideas are heard and understood in the boardroom. Corporate success will attract a diversity of talents onto a company board; particularly during rapid growth, it is vital to retain a

[56] http://www.ktnetworks.co.uk/epicentric_portal/site/KTN/?mode=0
[57] http://www.ktponline.org.uk/
[58] http://www.nmo.bis.gov.uk/content.aspx?SC_ID=453
[59] http://www.governmentchemist.org.uk/

top-level science ethos, and tax incentives could play a part. The most transparent measures on which to base incentives may be the R&D budget itself, and the projected value that it will add to the company (over, say, five years).

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?
Our finance team is willing to provide further input on the matter of initiatives for supporting innovative business.

Past funding initiatives such as SMART, SBRI, Link and Faraday, and all that TSB now embraces, have been helpful in encouraging innovations in established areas of technology. Gaps remain in sustained support for disruptive technologies - those innovations capable of provoking a paradigm shift in industrial practice. We have recently partnered with a US company that has developed an exciting new measurement platform, and look on with envy at the near decade of full grant funding they have received through Government agencies. This would simply not have been possible within the UK.

Going forward, a key criterion for targeting UK initiatives might be assured breadth of impact: whether a business has credible potential to deliver benefits distributed widely over the stakeholding public. Innovation has particular potential where it leads to tangible products or services that can readily be tailored to supply diverse yet enduring areas of demand, such as advanced healthcare, wholesome and nutritious food, safe consumer goods, a secure society and a non-toxic environment. This approach to prioritising support would help ensure that UK businesses live up to their promise by finding sustainable markets - and continue to repay the Exchequer for many years to come.

The ecology of research funding

15. How do we maintain an appropriate funding balance between curiosity-led, response-mode research, and more targeted or programmatic funding?
There is a strong case for harnessing advisory input representing a broad spectrum of views (industry, policy and academic), aligned to a clear UK strategy on wealth creation and quality of life. Advisory groups can help provide practical opportunities for dissemination and exploitation as and when required, whether or not the starting proposals are impact-driven.

Independent peer review can add depth and rigour to the decision-making process. Independent scientists are likely to be fascinated by curiosity-led research and to grasp its intrinsic value. However, they also possess the detachment to weigh intrinsic merits alongside the more targeted outcomes that may be offered by alternative projects, programmes and high-level budget allocations. The peer review mechanism needs robust safeguards against conflicts of interest, so it will often be appropriate for scientists from outside the academic ring-fences to appraise proposals.

16. 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?
This is a far horizon in a fast-changing world, but we envisage that research funders might work together even more closely to ensure that cross-cutting strategic challenges are addressed - perhaps along the lines of the Biotechnology and Biological Sciences Research Council's proposed Healthy Ageing Research and Technology Club[60] - and the optimal blend of skills and expertise can be applied to emerging opportunities which call for multidisciplinary effort. This flexible approach may entail a rollback of the trend toward establishing research centres with specific missions, as such structures can sometimes run the risk of complacency and of overlooking extramural talent.

As global challenges intensify, we expect to see increased emphasis on funding research into emerging and disruptive technologies, coupled with the means of extracting benefit across a wide front. NMO's role in validating innovation will focus on fitness for purpose - demonstrating whether research outcomes are ready for industrial application and helping to maximise their impact across a wide front. Measurement science will itself be increasingly impact-driven. For example, advances in point-of-use

[60] http://www.bbsrc.ac.uk/business/collaborative_research/industry_clubs/ageing/index.html

monitoring technologies will benefit care in old age, the safety of globally traded products, and the fight against crime. Research into cost-effective yet high performance measurement techniques will yield data needed to assess the complex range of toxic threats to our environment more objectively.

Innovation can currently be stifled by EU stipulations concerning qualifying institutions and the percentage of research costs that may be funded. As overseas competition powers up, funding mechanisms will need to become more flexible, for example by encouraging companies to deploy unique expertise or essential scale-up facilities in fields which may offer them only minimal, indirect or uncertain returns.

In a world driven by knowledge, innovation and the global challenges arising from our success as a species, international treaties and EU legislation can be expected to rely ever more closely on science. The associated requirements might be effectively serviced by a cross-cutting research institute for science underpinning regulation (ISUR), established to provide objective data and expert opinion at arm's length from regulator and regulated.

Let us be clear that the world could be very different in 20 years time, and the funding landscape needs to respond to requirements and challenges as they emerge. Given the pace of global competition, the UK dare not vacillate over change and improvement. Once we are set on a sound course, adherence to a five-year structural review cycle would promote confidence and stability, whilst providing enough flexibility to adjust to unfolding circumstances. In 20 years time, we hope to see well-managed provision of funding that is more joined up, with soundly-resourced and facilitated technology transfer. Funds would be targeted to give the biggest bang for the buck over short, medium and long-term horizons.

17. 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?

Departmental spending on innovation should reflect public understanding of the word, with a clear focus on extracting benefit from the science base.

Established institutions such as the National Health Service have a responsibility to the taxpayer for cost-effective procurement. Consequently they may need to embrace the outside world by challenging industry to improve on the way key R&D requirements are being met.

National laboratories should wholeheartedly welcome all opportunities to support and contribute to the UK science base. For example, the national measurement laboratories can:

- Help with the development, validation and market entry of innovative technologies
- Supply tailored measurement services and infrastructure, such as 'designer' reference materials targeted at particular applications
- Co-ordinate the development of guidance on measurement science needed in specific fields, such as on omics for advanced healthcare, to comply with regulation and expand into new markets
- Provide peer review for research programmes, project proposals and publications that is both independent, and visibly so
- Provide a national focal point or championing role for knowledge exchange networks, at the interface between science, industry and government.

At a wider level, we in the national measurement laboratories share certain responsibilities with our sister institutions, for instance those facing the nuclear and defence sectors: we need to be responsive to UK needs, and provide world-class support to stakeholders in a way that is easy and understandable to access.

Thank you again for the opportunity to participate in the Fruits of Curiosity inquiry. We would welcome further dialogue, particularly as it is clearly of value to build a UK consensus on many of the issues raised.

Yours sincerely

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