Vision

for science and
mathematics education

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Vision for science and mathematics education
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Cover image: ‘Making lightening’ at the Royal Society Summer Science Exhibition, 2012. Exhibit: *Listening to Storms and Volcanoes*, by the Met Office.

Contents

Foreword

The ability of people to understand the world in which they live and work increasingly depends on their understanding of scientific ideas and associated technologies and social questions. For most people such understanding will come mainly through education. This report sets out the Royal Society's vision for science and mathematics education over the next 20 years. It is about how such education can enable people to make informed choices, empower them to shape scientific and technological developments, and equip them to work in an advanced economy. Such outcomes are necessary if the UK is to maintain its position as a world leader in science and engineering and achieve economic growth and to secure the health and well-being of the nation.

The report, a product of a major programme of work over the past two years, also outlines how the vision can be achieved. The programme was led by a committee with a wide span of expertise, and it was distinguished by its breadth of engagement with individuals and groups concerned with science, mathematics, teaching, and education systems.

The report addresses questions of importance and urgency. I hope you will find it thought-provoking and compelling.

Paul Nurse
President of the Royal Society


Differences

Science and mathematics education for 2030

Science and mathematics are at the heart of modern life. They are essential to understanding the world and provide the foundations for economic prosperity.

The UK is a world leader in science and engineering. To maintain and capitalise on this position, the UK needs to strengthen its science, technology, engineering and mathematics (STEM) education.

Our Vision aims to raise the general level of mathematical and scientific knowledge and confidence in the population. Scientific discovery and technological innovation can provide solutions to challenges such as scarcity of food and water, energy supply and security and climate change, but they also raise social and ethical dilemmas. All citizens need the skills and knowledge to be able to make informed decisions about how society handles these issues.

In addition, our Vision seeks to link people's learning and skills to the current and future needs of the economy. Science and technology open doors to jobs in many sectors where the analytical and problem-solving skills acquired by studying mathematics and science are greatly prized. These skills are vital if the UK is to remain competitive internationally and to ensure that people are productively employed throughout their lives.

There is excellent practice in primary and secondary schools across the UK's four nations. Our Vision for science and mathematics education from 5–18 years of age offers a way to build on these foundations.

Firstly, in order to ensure young people have a broad and balanced education through to age 18, baccalaureate-style frameworks should be introduced. Inspirational science and mathematics curricula should be placed at the heart of these, and should emphasise practical work and problem-solving. The new frameworks should incorporate subjects in the arts, humanities and social sciences and place equal value on vocational learning.

Secondly, education systems need to provide stability for the curriculum and its assessment in order to support excellent teaching and enable innovation. To achieve this, new, independent, expert bodies that draw on the wider STEM professional community need to be created in England and Wales to determine curricula and assessment in STEM subjects. Existing infrastructures in Northern Ireland and Scotland should be similarly supported.

Left
Young person at the Royal Society Summer Science Exhibition, 2012. Exhibit: *DNA is not your only destiny; epigenetics behind the scenes.*

Thirdly, many more inspiring teachers will be needed. For this to happen, a sustained effort is required to recognise their professionalism and raise their status. To keep up-to-date and maintain a passion for their subject, teachers need time and resources to undertake subject-specific professional development, with this being linked to career progression.

In order to realise our Vision, we envisage a significant role for the science, technology, engineering and mathematics professional community including:

- playing a leading role in the proposed independent expert curriculum and assessment bodies;
- championing more and better quality educational research;
- supporting excellence in teaching science and mathematics;
- embracing teachers as an integral part of the community; and
- providing regular opportunities for professional development.

Our Vision takes the long view but recognises that there is both urgency and great opportunity for Governments to act now. There is a persistent dearth of young people taking science, technology, engineering and mathematics qualifications after the age of 16 across the UK. Employers report that the skills and numbers of students leaving education do not fully match their needs. And estimates suggest that one million new science, engineering and technology professionals – including technicians – will be required in the UK by 2020.[1]

This is an exciting and important time in education as countries world-wide recognise the importance of high-level skills and their impact on economic growth, well-being and prosperity. Digital technologies, cross-disciplinary skills and the age of big data will all have a significant impact in the classroom and on teachers. Mathematics and science must be placed at the heart of education systems. This will help to underpin the future prosperity of the UK, ensure the UK maintains a globally competitive science and engineering base and support the development of a more informed and equitable society.

1 Royal Academy of Engineering 2012 *Jobs and growth: the importance of engineering skills in the economy*. London: Royal Academy of Engineering.

Our Vision and recommendations

OUR VISION

All young people study mathematics and science up to the age of 18.

Create new baccalaureate-style frameworks that encompass vocational and academic learning across a broad range of subjects to age 18.

RECOMMENDATIONS

- Develop rigorous new post-16 courses and qualifications in mathematics, science, engineering and technology to engage students who are studying non-STEM subjects at school or who are training in the workplace, ensuring these meet the changing needs of employers.
- Increase the amount of time and money invested in practical and problem-solving work in science and mathematics education for 5–18 year olds, through access to adequately resourced laboratories and well-trained teachers.
- Extend the age at which students leave formal education or training to 18 in Northern Ireland, Scotland and Wales.

OUR VISION

Curricula and their assessment are stabilised and support excellent teaching and learning.

Use the expertise and independence of the STEM professional bodies, under strong overarching bodies, to stabilise the curriculum and assessment, providing quality and coherence in 5–18 science and mathematics education.

RECOMMENDATIONS

- Establish new, independent, expert bodies in England and Wales, and enhance existing structures in Northern Ireland and Scotland, to provide stability in curriculum and assessment and allow teachers space to innovate in their teaching.
- Commit to invest in these bodies long-term to enable STEM experts, including employers, to contribute their knowledge and experience.

OUR VISION

Teachers have high professional status and there is a strong supply of science and mathematics specialists.

Widen access to science and mathematics teaching and enhance their appeal to prospective entrants and returners by expanding the STEM professional community's role in recognising professionalism in teaching.

RECOMMENDATIONS

- Require all school and college teachers to work towards a suitable teaching qualification to ensure they are experts in teaching as well as in their specialist subject.
- Retain STEM technicians in schools and colleges on permanent and well-paid contracts.
- Make subject-specific professional development a core requirement for teachers and technicians and link this to career progression.
- Invest over the long term in national infrastructures which provide access to subject-specific professional development for all STEM teachers and technicians.
- Ensure that every primary school has, or has access to, at least one subject specialist teacher in both science and mathematics and that all post-primary science and mathematics lessons are taught by suitably qualified subject specialists.
- Train and reward teachers to engage fully with digital technologies to improve students' experience of, and attainment in, science and mathematics.

OUR VISION

Students understand the significance of STEM through better careers awareness and guidance.

Maintain investment in large-scale, national programmes and events, delivered locally, which provide students with STEM role models and help teachers and families to develop better engagement with academia and industry.

RECOMMENDATIONS

- Build careers awareness from primary school onwards by giving children exposure to role models, such as professional scientists, engineers and technologists.
- Make careers information, advice and guidance from early secondary onwards an essential part of the school/college week.
- Increase parents' understanding of how STEM offers many and varied employment opportunities for all children, regardless of their social or economic status.

OUR VISION

The success of students, teachers and education systems is judged through appropriate and broadly based assessment and accountability measures.

Ensure teachers have an increased role in assessing student achievement in public qualifications. Judge the health of the school and college systems through broader measures including ones that reflect the features of high quality STEM education.

RECOMMENDATIONS

- Entrust teachers with increased responsibility for assessing students' achievements.
- Place practical work and problem-solving at the heart of good assessment of science and mathematics.
- Use a wider set of measures than examination performance to make more informed judgements about the quality of a school or college.
- Measure the quality of science and mathematics provision in schools and colleges through specific STEM-related indicators, such as tracking the number and diversity of students taking STEM qualifications to 16 and post-16.
- Require all school and college governing bodies to have at least one member with STEM subject expertise.
- Increase the emphasis in school and college inspections on identifying and sharing good practice.

OUR VISION

Education policy and practice are better informed by evidence.

Enhance collaboration and communication between science and mathematics education researchers, scientists and mathematicians, teaching professionals, policy-makers and the public.

RECOMMENDATIONS

- Establish agreed standards for educational research to ensure good practice and to give users confidence in its results.
- Invest in education research and test and evaluate new programmes prior to rolling them out nationally.
- Encourage professional and learned STEM bodies to embrace teachers and STEM education researchers in their networks.

Timeline for achieving our Vision

	NOW	IN 5 YEARS	IN 10 YEARS	IN 15 YEARS	IN 20 YEARS
CURRICULUM	Across the UK too few students are inspired to study mathematics and science beyond age 16 for the UK to sustain its competitive economy.	Teachers, employers, Governments and the education community have worked together to design and introduce new baccalaureate-style frameworks, with the involvement of those from the STEM community and industry. Students understand the significance of STEM in the real world through better careers awareness and guidance. Independent curriculum and assessment bodies are established in England and Wales.	High-quality technical and academic courses are part of the new curricula and are respected equally. All young people study appropriate mathematics and science in baccalaureate-style frameworks, up to the age of 18.	The independent curriculum and assessment bodies established in England and Wales, and enhanced existing structures in Northern Ireland and Scotland have brought stability to curricula. All curriculum and assessment bodies across the UK use evidence and pilots to implement policy changes.	
ASSESSMENT	Assessment for public qualifications is mainly by external exams. Teachers are not trusted to conduct high-stakes assessments.	Some teachers have been trained to become expert assessors and to use these skills as part of the implementation of the new curriculum.	Teacher assessment and moderation are more common and trusted components of assessment for public qualifications. External assessment is still used, largely at key transition points.	The move towards more teacher assessment and moderation is maintained.	Teachers are responsible for assessment of public qualifications. Teacher assessment is trusted, understood and respected by parents, the public and employers.
ACCOUNTABILITY	Schools and colleges are accountable to an inspection regime that is seen as punitive rather than supportive. Performance tables mainly report examination results.	Work to design better means of holding schools and colleges to account begins. Schools, colleges and other interested parties are fully involved.	Every governing body has someone responsible for STEM subjects. Schools are held accountable for a wider range of measures than examination performance.	Inspection acts as a positive force for improvement and innovation and is welcomed by school and college leaders.	The success of schools, colleges, students and teachers is judged by an effective and appropriate accountability system that reflects the features of high-quality STEM education.
TEACHER PROFESSIONALISM	There are shortages of science and mathematics teachers in areas of the UK. Many teachers do not engage regularly in subject-specific professional development.	Teachers have more opportunities to take part in professional development and are helped by the STEM community and industry to use a wider range of teaching methods to inspire students.	It is mandatory for teachers to engage regularly in subject-specific professional development throughout their teaching careers.	All teachers regard professional development as a career-long necessity for practice. Regular subject-specific professional development has had a positive impact on students' learning.	Teaching is a highly regarded career with a high professional status. This encourages a strong supply of science and mathematics teachers.

Education policy and practice are better informed by evidence

Part one
Education in changing times

Science and mathematics education prepares young people to navigate a rapidly changing world and provides the foundations for economic prosperity.

Left
Learning through technology. © Mint Foto

Education in changing times

> "By 2030 we can expect a billion more people to be on the planet, world food requirements will rise by 38%, world water demand will exceed supply by a gap of 40%, and world energy consumption is forecast to increase by 54%. These, together, amount to a 'perfect storm'."

Paul Nurse, President of the Royal Society, speaking at Seoul National University, March 2014.

1.1 The importance of education

Education matters because it provides young people with knowledge and understanding of how the world works and opportunities to live rewarding and worthwhile lives. Young people need the best possible education if they are to thrive in a rapidly changing world and if the UK is to have a flourishing economy.

Outstanding education systems also help to nurture a more resilient society, increase social mobility and employment, and tackle high levels of deprivation and child poverty.[2,3] Of the seven 'keys' to enhancing social progress identified by the UK's Social Mobility and Child Poverty Commission, three are directly concerned with education:

- 'Adults being supported to be warm authoritative parents actively engaged in their children's education, particularly in the early years;
- High-quality schools and teachers relentlessly focused on raising standards, building social skills and closing attainment gaps;
- Clear accessible routes into work for those pursuing both vocational and academic education and training.' [4]

In the increasingly populous and interconnected world of the 21st century, and with the balance of economic power swinging from the West to the East, young people in the UK are likely to face stiffer competition for education, training and employment opportunities.[5] They will need to develop flexible minds, resilience – to enable them to adapt to and embrace change – and a lifelong interest in and capacity for learning.

New digital technologies are set to have an increasingly significant impact on education and, in the short term, efforts will be needed to ensure that everyone is digitally connected and can access open data and knowledge.

Large datasets and the rise of open academic publishing have the potential to transform teaching and employment. These technologies are beginning to change where and how people learn. Children and teachers are beginning to access cloud-based technology for exciting practical experiments, and virtual interactive demonstrations broadcast from a classroom, laboratory or public arena can involve an audience of thousands across the country and further afield, enabling experiments to be carried out on a previously unimaginable scale.[6,7] In its attempts to gain a competitive advantage over other nations, the Government of Estonia is trialling an entirely computer-based approach to teaching mathematics, where students are

2 Taylor, M, Haux, T & Pudney, S 2012 *Skills, employment, income inequality and poverty: theory, evidence and an estimation framework*. York: Joseph Rowntree Foundation.

3 The Rt Hon the Lord Heseltine of Thenford CH 2012 *No stone unturned in pursuit of growth*. London: Department of Business, Innovation and Skills.

4 Social Mobility & Child Poverty Commission 2013 *State of the Nation 2013: social mobility and child poverty in Great Britain*. London: The Stationery Office.

5 Royal Society 2012 *People and the planet*. London: Royal Society.

6 Davies, P, Kent, G, Laurillard, D, Mavrikis, M, Noss, R, Pratt, D & Price, S 2013 *The impact of technological change on STEM education*. Report for the Royal Society. (Hereon referenced as Ev. 6, as in Appendix 7.2, published online at www.royalsociety.org/vision)

7 Evershed, J, Forwood, S & Rutherford, A 2013 *What are the implications of psychology and neuroscience research for STEM teaching and learning?* Report for the Royal Society. (Hereon referenced as Ev. 5, as in Appendix 7.2, published at online at www.royalsociety.org/vision.)

challenged to solve problems in probability and statistics in an online environment.

Science, technology, engineering and mathematics (STEM) education has a vital role to play in developing flexibility and resilience in the new Information Age, providing young people with knowledge and skills that are valuable in life and work and routes to careers in economically important sectors, innovation and manufacturing.[8]

1.2 The educational and economic importance of science and mathematics

Science and mathematics are central to understanding and interpreting many of the global challenges the world faces, from water, food and energy supply to climate change and population growth. Developing and applying technologies to address these challenges is crucial for improving the quality of life for billions across the planet and for economic prosperity.

Being educated to a high standard in mathematics and science is likely to maximise young people's chances of success, both personally and professionally, in an increasingly competitive society. As well as offering insight into the wonders of nature, a sound education in these subjects is essential to achieving progress as a modern democracy, one that is capable both of developing creative scientists and engineers and astute citizens. In science and mathematics, perhaps more than any other aspect of education, there is a fortunate coincidence between the intellectual and cultural needs of the individual and the economic needs of the nation.

1.3 The global focus on improving education

It has been estimated that one million new science, engineering and technology professionals including technicians will be required in the UK by 2020.[9] However, within the engineering, high-tech, information technology (IT) and science sector of the economy, around one in four employers have problems recruiting appropriate STEM skilled employees, and this is set to reach two in five over the next three years.[10] A recent report on the future of work in 2030 suggested: 'Technological growth, and the accompanying changes in business models, make the continuous adaptation of skill sets absolutely fundamental for successful participation in the labour market'.[11]

The UK is not alone in facing these skills challenges. The global response has been to review and reform education systems. The establishment of the Programme for International Student Assessment (PISA)[12] and other global rankings of education systems has seen nations competing to be top of the international education league tables, using these to see how their own country fares and to learn from each other.

These global rankings are controversial because of the way they are put together and reported, yet they have become a means for pushing forward rapid change in education policy around the world. Indeed, slippage in the UK's place in the rankings – particularly

One million new science, engineering and technology professionals will be required in the UK by 2020.

In science and mathematics there is a fortunate coincidence between the intellectual and cultural needs of the individual and the economic needs of the nation.

8 See http://company.wolfram.com/news/2013/estonia-named-first-computer-based-math-education-country/, accessed 11 November 2013.

9 *Op. cit.*, note 1.

10 Confederation of British Industry 2013 *Changing the pace. CBI/Pearson education and skills survey 2013*. London: CBI/Pearson.

11 UK Commission for Employment and Skills 2014 *The future of work: jobs and skills in 2030*. London: UKCES.

12 PISA is a triennial international survey administered by the OECD that aims to evaluate worldwide education systems by testing the knowledge and skills of 15-year-old students in reading, mathematics and science.

in science and mathematics – has been cited by government when undertaking the most recent National Curriculum review in England and that ongoing in Wales.

Nations have realised that general improvement in educational outcomes – and particularly in STEM subjects – can bring great economic benefit. Enhancing national competitiveness is of major interest to all governments, and many – for example, in Asia – have prioritised investment in STEM education in their national education strategies.[13] As governments realise that growth and competitive advantage can only be sustained through a highly educated and skilled population, the global appetite for educational reform seems set to increase. There are, therefore, likely to be significant consequences for people and for the UK if our education systems do not equip young people to deal with the challenges of the world in 2030 and beyond. Valuable talent will be wasted, and the UK will fall behind in a more scientifically and technologically advanced world.

1.4 The need for improvement in science and mathematics education

Although the UK's education systems include some of the best schools and colleges in the world, there is room for improvement. For instance, one in five children in England leaves primary school not having gained the expected standards of literacy.[14] In recent evidence gathered from inspections of English schools, inspectors found that too many able students across the 3–16 age range are underachieving in mathematics and that 'many more' could gain the highest grades at GCSE and be better prepared to continue to A-level.[15] In Wales just 53% of those taking mathematics GCSE attained a grade C or above in 2013,[16] compared with 65% in Northern Ireland.[17]

It is not surprising, therefore, that progression to post-16 studies in science and mathematics is generally poor across the UK. Whilst there have been substantial A-level entry increases being recorded in biology, chemistry and mathematics, there has been only a modest overall increase in the number of physics A-level entries and a substantial fall in entries to A-level computing and ICT.

13 *The world towards 2030: drivers of change – education*. The Futures Company, 2013. (Published online at www.royalsociety.org/vision)

14 Ofsted 2012 *Driving up standards of literacy*. London: Ofsted. (See http://www.ofsted.gov.uk/news/driving-standards-of-literacy, accessed 18 October 2013.)

15 Ofsted 2012 *Mathematics made to measure*. Messages from inspection evidence. London: Ofsted.

16 BBC online 22 August 2013 GCSE maths and science results in Wales fall following changes. (See http://www.bbc.co.uk/news/uk-wales-23791640, accessed 2 May 2014.)

17 NIdirect 2013 Ministers welcome GCSE results. (See http://www.northernireland.gov.uk/news-de-220813-ministers-welcome-gcse, accessed 2 May 2014.)

TABLE 1

Comparison between 2003 and 2013 of the number of UK A-level entries in mainstream science and mathematics subjects as a percentage of the total number of entries across all subjects

Subject	No. of entries (2003)	No. of entries as a percentage of entries across all subjects (2003)	No. of entries (2013)	No. of entries as a percentage of entries across all subjects (2013)
Biology	51,716	6.9	63,939	7.5
Chemistry	36,110	4.8	51,818	6.1
Physics	31,543	4.1	35,569	4.2
Mathematics	50,602	6.7	88,060	10.4
Computing and ICT	28,175	3.8	14,177	1.7

Source: JCQ.
Note: 2003 was the first year that results were available for computing and ICT.

More worryingly in recent years, the proportions of the post-16 student cohorts completing examinations in mainstream biological sciences, chemistry and physics A-levels have been very low across England, Wales and Northern Ireland (28%, 27% and 37%, respectively, in 2008/09), and considerably lower than the equivalent proportion of the Scottish cohort (50% in 2008/09) taking Highers or Advanced Highers in these subjects.[18]

A particular concern is the persistently low numbers of girls pursuing physics and mathematics A-levels/Highers, which contrasts with their strong preference for the biological sciences. Girls accounted for 21% of all A-level physics entrants, 39% of A-level mathematics entrants and 29% of A-level further mathematics entrants across the UK in 2013.[19] The Institute of Physics has also reported that no single girl from 49% of coeducational maintained schools in England went on to take A-level physics in 2011.[20]

The low levels of post-16 participation in science and mathematics result in insufficient numbers of UK-domiciled STEM graduates and other skilled technical professionals to meet employers' needs. The underrepresentation of women in certain areas of STEM, in particular engineering,[21] is also of considerable

18 Royal Society 2011 *Increasing the size of the pool. A summary of the key issues from the Royal Society's 'state of the nation' report on preparing for the transfer from school and college science and mathematics education to UK STEM higher education*. London: Royal Society.

19 Joint Council for Qualifications 2013 Results 2013. (See http://www.jcq.org.uk/, accessed 13 May 2014.)

20 Institute of Physics 2012 *It's different for girls. The influence of schools. An exploration of data from the National Pupil Database looking at progression to A-level physics in 2011 from different types of school at Key Stage 4*. London: IoP.

21 Royal Society 2014 *A picture of the scientific workforce. Diversity data analysis for the Royal Society. Summary report*. London: Royal Society.

concern and has prompted this warning from Engineering UK:

'The continued inequality in the uptake and progression of women into engineering only serves to exacerbate the shortfall in the required supply of talented engineers and technicians and is detrimental to the competitiveness of the UK. By equalising labour force participation rates between men and women, the UK could increase GDP per capita growth by 0.5 percentage points per year, with potential gains of 10% of GDP by 2030'.[22]

It is clear therefore that these shortages will continue to have implications for the growing ambitions of the UK Government to develop and enhance a national industrial strategy.

1.5 About this report

This report considers what needs to be done to transform primary and secondary science and mathematics education across the UK over the next 20 years or so. It offers a view of whole education systems for 5 – 18 year olds from the perspective of professional communities in science, engineering and mathematics.

Undertaking to set out a vision for science and mathematics education with a 20 year horizon is ambitious and carries with it many challenges, not least that it is impossible to predict the future.

A further challenge for our Vision is that there continues to be a lack of high-quality educational research upon which to base judgements – an issue we address in the following section. Decision-making in education is therefore often based on political ideas about the rights of citizens, the role of the state and the kind of society citizens believe should be developed, rather than factoring in evidence about what works.

The report reflects independent evidence of the educational landscape as it is known today, expert opinion and, unusually for a scientific body, assertions based on values and judgements. There are some aspects of education where it has been necessary to set out principles based on beliefs, either because the evidence is not available, or because the principle is, by its nature, untestable. For example, statements about the best balance of subjects in the school curriculum need largely to be assertions of belief because of the difficulty of setting out notions of 'an all-round educated person' in a way that can be tested scientifically.

To achieve the most robust and far-reaching vision therefore, we have used a variety of tools to probe 'under the bonnet' of the UK's education systems. These have included:

- assessing national and international educational trends and likely influential drivers of change, such as the anticipated growth and impact of digital technologies, the rise of interdisciplinary research practices and the skill sets required in the economy;
- commissioning independent expert reviews in nine areas of educational research (see Appendix 7.2);
- organising a series of expert seminars and stakeholder consultation activities; and
- engaging in extensive dialogue across the UK's STEM education community.

22 Engineering UK 2014 *Engineering UK 2014. The state of engineering*. London: Engineering UK.

The resulting Vision is founded on the view that change to education systems should be made scientifically, by basing new educational strategies on evidence; piloting them on a small scale; evaluating their effectiveness before they are implemented universally; and investing in what works to improve and to innovate across systems.

We set out principles for how the UK's four education systems might achieve excellent science and mathematics teaching and learning, recognising that their implementation will vary according to the differing political, social and economic situations in each nation.

With England being the largest and most populous of the Home Nations (as indicated by the data in Appendix 7.7), we have sometimes focused on its specific needs. Nonetheless, the report's messages are equally relevant across all four nations of the UK – and beyond. However, the ways in which they are implementable necessarily vary from one jurisdiction to another. It is the broad principles that matter, and each jurisdiction – whether in the UK or further afield – should apply them in a manner suited to its particular circumstances.

In setting out ideas and principles, we do not include detailed implementation plans to deliver the Vision. This will require extensive further work – not least to determine how much funding is needed to realise our ambitions and from where it will be found. We remain firm in our view, however, that long-term investment in excellent science and mathematics education will deliver significant advantages to people, to society and to the UK economy.

We have concluded that although inspiring practices can be found all over the UK (some of which are illustrated in the report), some significant and entrenched problems, specific to the UK, need to be overcome. These include the ongoing persistent shortages of specialist science and mathematics teachers and, as shown in § 1.4, poor progression rates of students to post-16 science and mathematics studies that prevail across much of the UK.

At the root of these are educational issues of wider concern, such as the framework of compulsory education, the content of science and mathematics curricula, the relationship between schools and colleges and their local communities and a teaching profession that is worn down by continuous policy reform and narrow accountability measures. Solutions to these problems are offered – revitalising and stabilising curriculum frameworks; extending a broad and balanced education for all young people to age 18; ensuring teachers are free to teach creatively and that the profession is esteemed and respected.

Concerted action is needed now if the UK's education systems are to remain world-leading in the years to come. Whilst recognising a range of good practices and initiatives that are in place, we believe that these are insufficient to achieve the scale of the transformation required.

We fully acknowledge that our Vision for science and mathematics education can only succeed as part of systemic educational reform, that the proposals we make are complex, that some have implications for all subjects and for Higher Education, and that they cannot happen quickly. But the process of change must begin now – and urgently – if we are to inspire the next generations and prosper.

Educational reform should be based on evidence.

1.6 Building a sound evidence base for policy and practice

Education in the UK will benefit from a strong foundation on evidence, and the principle for basing education policy on research originally established in the early years of the Blair administration needs to be re-established. This requires collaboration between science and mathematics education researchers, scientists such as neuroscientists and psychologists, teaching professionals, policy-makers and the public. The small-scale survey undertaken among these communities for this project indicated strong support for this approach,[23] and the Education Endowment Foundation and The Sutton Trust, jointly designated by the UK Government in 2013 as one of the new What Works centres, are beginning to fulfil this function.

With its origins in the 1970s, science education research is a comparatively new and diverse field of enquiry.[24] Education research provides the underpinning evidence to improve education, but many of the studies commissioned for this project acknowledge sizeable gaps in knowledge and understanding. It is not clear what denotes high-quality educational research nor how it may be identified by those outside the education research community.

As the National Foundation for Educational Research (NFER) has acknowledged, the education research community needs to improve its communication with practitioners and policy-makers, and to establish agreed standards for educational research.[25]

For their part, policy-makers and independent intermediary organisations (including learned and professional bodies and independent commissioners of research) need to be conscious of the important role they have in building capacity of the UK's educational research base, which is small, especially in the STEM area.[26]

They should focus their efforts on:

- building capacity;
- commissioning research programmes designed with input from the teaching profession;
- ensuring that curriculum reforms are fully and properly piloted and evaluated;
- recognising the potential value of longitudinal research in informing policy and practice; and
- facilitating improved dialogue and, perhaps in particular, translating the findings of research using language appropriate for wider audiences including teachers and the public.

Repositories of high-quality research evidence, such as those held by the National STEM Centre, the National Centre for Excellence in the Teaching of Mathematics (NCETM) and the EEF, should be maintained, linked and readily accessible, especially by the teaching profession. There is a case that there would be benefits to the quality of STEM teaching if teachers could engage more in educational research, to improve their own practice or to participate in research projects led by others. This is already a growing expectation in other professions, such as medicine.

23 Ev. 5.

24 Jenkins, E W 2008 Research in science education: time for a health check? *Studies Sci. Ed.* 35, 1–25.

25 Durbin, B & Nelson, J 2014 *Why effective use of evidence in the classroom needs system-wide change*. Slough: NFER.

26 Halsey, K, Harland, J & Springate, I 2007 *Increasing capacity in STEM education research: a study exploring the potential for a fellowship programme*. Slough: NFER.

At present, teachers may find it difficult to engage with educational research, perhaps because:

- they do not know how to access educational research, identify whether it is high quality and robust or how to make best use of it to improve their teaching;
- the research may be difficult to sift, as it may not have been synthesised or translated for the practitioner;
- they do not have the time to engage with educational research.[27]

The responsibility for engaging teachers in educational research rests with the national education structures and with teachers themselves, as professionals committed both to their own professional development and to leading innovation across teaching. Leadership here needs to come from government, its agencies and the professional bodies. This includes the inspectorates, which should encourage involvement in randomised controlled trials and the use of evidence to improve practice.

Teachers and teacher educators should, as the NFER has argued, be equipped to conduct their own research, and there should be impetus for growing a high-quality education research community in the UK.[28] This community in turn should be recognised as a beacon of excellence that sets the international benchmark.

Governments should aim to integrate educational research into policy-making to support considered reform to the UK's education systems, for instance through the work of the new independent curriculum bodies proposed in part four.

OUR VISION

Education policy and practice are better informed by evidence.

Enhance collaboration and communication between science and mathematics education researchers, scientists and mathematicians, teaching professionals, policy-makers and the public.

RECOMMENDATIONS

- Establish agreed standards for educational research to ensure good practice and to give users confidence in its results.
- Invest in education research and test and evaluate new programmes prior to rolling them out nationally.
- Encourage professional and learned STEM bodies to embrace teachers and STEM education researchers in their networks.

27 *Op. cit.*, note 25.

28 *Ibid.*

Part two
Thinking scientifically and mathematically

Scientific and mathematical understanding is fundamental to fostering an inclusive and effective democracy. Science and mathematics should be key components of education, igniting curiosity as well as encouraging confidence and creativity.

Left
Students at Britannia Village Primary School exploring static electricity.

Thinking scientifically and mathematically

69%

say that scientists should listen more to what ordinary people think.

43%

say that they would like to know that the public are involved in the decisions made about science issues.

2014 Public attitudes to science 2014. Main Report. London: Ipsos Mori Social Research Institute.

Every member of society should be capable of balancing the benefits and risks of new science.

2.1 The importance of being able to think scientifically and mathematically

The previous part discussed the importance of ensuring that 21st century science and mathematics education keeps pace with a rapidly changing world. However, alongside its significant benefits, new scientific knowledge can bring risks and pose ethical dilemmas to society. It is essential for the maintenance of an effective democratic society that citizens should be capable of balancing the benefits and risks of new science and be able to reason mathematically.

A 2014 public attitudes to science study suggests that the public perceive controversial science topics to be dominated by partisan voices who often 'cherry-pick' evidence in support of their views.[29] A more healthy, inclusive debate, not limited to experts, about how knowledge is used and how potential applications are introduced and regulated, needs the contribution of scientifically and mathematically informed citizens.

People who think scientifically and mathematically are able to apply particular types of thinking (eg logical or critical thinking) learned in the classroom or the laboratory to the world beyond. This can help them to make informed judgements about contemporary scientific issues (such as how best to control TB in cattle) or decisions, for instance on medical treatments, based on an analysis of the risks. Over and above teaching the disciplines themselves, science and mathematics education in schools and colleges should show how these subjects contribute to the creation of wealth and the nation's good health. It should also demonstrate how science and technology pose threats to society and the importance of making choices informed by an understanding of risk and ethics.

The media also have a major role to play in the development of a more scientifically literate society. Most people access information about science through television, yet trust in science journalism is low and there is a desire from the public to hear more directly from scientists.[30]

29 Castell, S, Charlton, A, Clemence, M, Pettigrew, N, Pope, S, Quigley, Navin Shah, J & Silman, T 2014 *Public attitudes to science 2014. Main report*. London: Ipsos Mori Social Research Institute.

30 *Ibid.*

31 Cambridge Primary Review 2010 *Introducing the Cambridge Primary Review*. (See http://www.primaryreview.org.uk/Downloads/Finalreport/CPR-booklet_low-res.pdf, accessed 18 April 2014.)

2.2 Nurturing scientific and mathematical thinking

The development of scientifically and mathematically informed citizens is of such importance that it needs to begin in earnest during primary education in order to help ensure children have the best possible start in life and, as is discussed in part three, continue throughout secondary education.

The primary and secondary phases of learning are crucial periods in young people's development, and it is now understood that children's cognitive capacities – their ability to learn, think and reason – are the same as adults.[31] As a previous Royal Society review found, these periods are associated with changes in their ways of thinking, 'particularly the ability to deal with abstract concepts, [which] enable them to see connections within their rapidly expanding experience of the world around them'.[32] It is a time when children enjoy new experiences and want to be challenged, to learn things of relevance to their lives and to understand how everything fits together.[33]

Further research shows that the brain continues to develop throughout adolescence, and in particular 'those parts [of the brain] that are involved in decision-making, impulse control, planning and awareness'.[34] A strong scientific argument exists, therefore, for young people to maintain a broad curriculum to age 18, rather than specialise at an earlier age, and for them to continue studying science and mathematics to age 18. This would potentially enable a deeper understanding of these subjects to be gained as the brain matures.

The way that science and mathematics are presented is likely to have a long-lasting impact on young people's attitudes to these subjects.

Good primary science education, for instance, 'ignites pupils' curiosity and offers opportunities to develop their observation, questioning and reasoning skills whilst increasing their appreciation, knowledge and understanding of the world around them and stimulating a lifelong interest in science'.[36] Similarly, good primary mathematics will 'encourage and enable their pupils to think mathematically and be creative and confident in using mathematics from the start of their education'.[37]

84%
agree that science is such a big part of our lives that we should all take an interest.

72%
agree that it is important to know about science in their daily lives.

55%
did not feel informed.

2014 Public attitudes to science 2014. Main Report. London: Ipsos Mori Social Research Institute.

"With primary science I know for a fact it is a lot easier to grasp concepts at an earlier age and then move on to the complicated things in secondary science."

Young person[35]

32 Royal Society 2010 *Science and mathematics education, 5–14. A 'state of the nation' report*. London: Royal Society.

33 QCDA 2009 *Consultations with pupils on the new primary curriculum*. London: QCDA 2009.

34 Professor Sarah-Jayne Blakemore, personal communication, 25 February 2014.

35 Murray, I & Reiss, M 2005 *The student review of the science curriculum*. London: Institute of Education.

36 Society of Biology 2014 *The importance of biology in the primary curriculum: engaging learners in the life sciences. Position statement on primary science*. London: Society of Biology. (See https://www.societyofbiology.org/images/SB/FINAL_SB_Position_statement_on_primary_science.pdf, accessed 28 April 2014.)

37 CfBT 2012 *Enhancing primary mathematics teaching and learning*. London: CfBT.

Science education should enable young people to appreciate that:

- good science is based on reproducible observation and experiment, taking account of all evidence and not cherry-picking data;
- scientific issues are settled by the overall strength of that evidence, combined with rational, consistent and objective argument;
- science has the ability to prove that something is not true – that if a repeatable observation or an experimental result does not support a specific idea, then the idea has to be rejected or modified and then tested again;
- science is dynamic. Knowledge is always subject to challenge from new evidence and must accommodate whatever innovations in science and mathematical thinking and understanding arise in the future.

Mathematics education should nurture students' ability to think mathematically and to experience mathematics as a subject in itself and as a highly interconnected subject. Mathematics has relevance not only across the sciences, but also in arts and humanities and to people's everyday lives and future career aspirations.

As the Advisory Committee on Mathematics Education has advised, mathematics education should enable young people to:

- 'experience mathematics as a highly interconnected subject [through which] they reason mathematically and can identify and conjecture patterns, relationships and generalisations;
- develop mathematical fluency, conceptual understanding and can select appropriate techniques to solve problems in a range of mathematical, educational and general contexts;
- interpret and evaluate mathematical solutions, moving freely between verbal, graphical, diagrammatic and mathematical representations of a situation; and
- communicate mathematical findings clearly and effectively and evaluate different situations.'[38]

Science and mathematics education that furnishes young people with these forms of thinking, knowledge and skills will help them become scientifically and mathematically informed (Box 1).

38 Advisory Committee on Mathematics Education 2014 *A blueprint for mathematics education*. London: ACME.

BOX 1

What it means to be scientifically and mathematically informed within this report

A scientifically informed individual:

(i) understands scientific theories and concepts and that these are subject to challenge and change as new evidence arises;

(ii) can think and act scientifically (eg using hypotheses to test and solve problems while also using scientific knowledge) and uses essential reading, writing, mathematical and communication skills to analyse scientific information accurately;

(iii) makes informed interpretations and judgements (eg risk assessment) about scientific information and the world at large as well as engaging constructively in debate on scientific issues;

(iv) is able to apply scientific knowledge and understanding in everyday life; and

(v) maintains curiosity about the natural and made worlds.

A mathematically informed individual:

(i) understands mathematical concepts and recognises when they are present;

(ii) can think and act mathematically (eg applying knowledge and transforming methods to solve problems), uses mathematical skills and forms of communication to analyse situations within mathematics and elsewhere;

(iii) can make informed interpretations of information presented in a mathematical form and use it to engage constructively in debate on scientific and other issues;

(iv) is able to apply mathematical knowledge and understanding in everyday life; and

(v) maintains curiosity in mathematical concepts, and in other phenomena understood from a mathematical perspective.

2.3 Challenges to developing a scientifically and mathematically informed society

A number of surveys have suggested that young people see the importance of science and mathematics.[39] In a visit to the Big Bang Fair[40] for this project, young people had no difficulty in suggesting why it is important to learn science (Box 2).

Nonetheless, evidence suggests that many young people's positive attitudes to science and mathematics early in their education do not translate into a desire to study them later on.[42, 43, 44] Students in their last years of primary school tend to have significantly less positive attitudes to science than their younger peers, paralleling a similar decline in attitudes to both reading and mathematics with increasing age.[45]

BOX 2

Some young people's views on the importance of learning science[41]

"New energy solutions."

"Everything we do today involves science, so science is extremely important. For example, if someone wanted to be a hairdresser, whatever do they know what [*sic.*] goes into the hair dyes? That's all chemistry isn't it."

"You can get a lot of jobs out of it."

"I think it's going to cure a lot of people."

"Food sources are running out. We won't have enough protein. Science is probably going to find a new source of protein… a new humane way of producing that on a large scale."

39 For instance, the Wellcome Trust Monitor and King's College London's ASPIRES project. For a review, see also Bennett, J, Braund, M & Sharpe, R 2013 Student attitudes, engagement and participation in STEM subjects. Report for the Royal Society. (Hereon referenced as Ev. 3, as in Appendix 7.2, published online at www.royalsociety.org/vision)

40 The Big Bang Fair is the UK's biggest annual celebration of science, engineering, mathematics and technology.

41 See also video footage at: https://royalsociety.org/vision.

42 Reid, N & Skryabina, E A 2002 Attitudes towards physics. *Res. Sci. Technol. Educ.* **20**, 67–81.

43 Ev. 3.

44 King's College London 2013 *ASPIRES. Young people's science and career aspirations, age 10–14*. London: Department of Education & Professional Studies, King's College London.

45 Wellcome Trust 2008 *Perspectives on education. Primary science*. London: Wellcome Trust.

This situation worsens when one factors in ethnicity and gender. A recent large survey of 11 year olds in England showed that aspirations vary among children of differing ethnicity, with Black Caribbean students being much less likely to express aspirations to follow a career relating to science than their Asian peers.[46]

More widely, although over 80% of 460 teenagers aged 14 – 18 interviewed by the Wellcome Trust believed science was a good sector to work in,[47] only some 38% of similarly aged people questioned in a separate survey on behalf of Engineering UK picked a subject related to STEM as their favourite.[48]

Young people and parents often perceive science to be a 'hard' subject, suitable for only the most able pupils, and that scientists are 'mostly white, male and middle-class',[49] leading many young people to feel that it is not for them. Such an attitude is reinforced from an early age, with many children's books depicting scientists as fitting this stereotype.[50]

Students are also often unaware of the transferability of STEM skills and the range of careers that STEM qualifications can lead to.

These issues are particularly acute for families with a low level of qualifications, knowledge, and connections with science.[51] In fact, fewer girls pursue physics because of influence from family members and a lack of knowledge and understanding of what physics is and the career options that studying it can lead to.[52]

21%

of the people in the UK workforce need scientific knowledge and training to do their current jobs.

A picture of the UK scientific workforce, The Royal Society. (May 2014)

46 *Op. cit.*, note 44.

47 The Wellcome Trust Monitor 2012, table 228. (See http://www.wellcome.ac.uk/About-us/Publications/Reports/Public-engagement/WTX058859.htm, accessed 29 January 2014.)

48 Engineering UK 2013 *2013 engineers and engineering brand monitor – executive summary. Prepared for Engineering UK by IFF Research*. (See http://www.engineeringuk.com/_resources/documents/Engineers_and_Engineering_Brand_Monitor_2013_Executive_Summary.pdf, accessed 12 May 2014.)

49 *Op. cit.*, note 12.

50 Terras, M 2014 *Male, mad and muddleheaded: academics in children's picture books*. Blog, 5 February 2014. (See http://melissaterras.blogspot.co.uk/2014/02/male-mad-and-muddleheaded-academics-in.html, accessed 2 May 2014.)

51 Parliamentary Office of Science and Technology 2013 *STEM education for 14–19 year olds*. POSTnote no. 430. Also, *op. cit.*, note 44.

52 See http://www.iop.org/policy/diversity/initiatives/ethnic/page_42663.html, accessed 2 May 2014.

Part three
Placing science and mathematics at the heart of education

A bold new approach to science and mathematics curricula is needed, with all young people studying science and mathematics to age 18. New baccalaureate-style frameworks valuing vocational and academic learning as well as apprenticeships will support this approach.

Left
Hoberman sphere helping to illustrate mathematical thinking at Copland Community School.

Placing science and mathematics at the heart of education

3.1 New baccalaureate-style educational frameworks across the UK

The issue of breadth versus depth in education has been long-debated in the UK, and is closely tied to arguments around the purpose of education and the extent to which, and when, young people should be able to exercise choice over their studies.

In particular, post-compulsory education in the UK has been chiefly concerned with gaining passage to Higher Education. For over 60 years, the A-level system in place across England, Northern Ireland and Wales has encouraged specialised learning of a small number of subjects (three, on average, in recent years). In Scotland, a system of Highers has existed since 1888, involving the study of five subjects, on average, but to a less advanced level than A-level.[53] Alongside both systems there has been an alternative diverse provision of post-15/16 vocational qualifications, generally regarded as being '"second class" and less worthy'.[54]

These systems may have largely benefited the minority of the population destined for academic study, but they have failed to meet the needs of the vast majority of young people and not necessarily best served those of employers. Not surprisingly, the education and employment communities have been calling for these challenges to be addressed, and in England this is leading to the establishment of new academy schools in the form of University Technical Colleges (UTCs) (Box 3) and Studio Schools (Box 4).

In England, there is a growing consensus among employers and educators that the current A-level system should change into a baccalaureate-type system akin to that found in many (eg continental) education systems.[55]

53 The current Higher and Advanced Higher courses were introduced in 1999 as part of the Higher Still reforms, replacing the Higher Grade and Certificate of Sixth Year Studies (CSYS). See UCAS tariff (http://www.ucas.com/how-it-all-works/explore-your-options/entry-requirements/tariff-tables/Scottish-Highers), accessed 21 February 2014.

54 Royal Society 1991 *Beyond GCSE*. London: Royal Society.

55 Anderson, R 2014 *Making education work. A report from an independent advisory group chaired by Professor Sir Roy Anderson*. London: Pearson.

BOX 3

University Technical Colleges[56]

UTCs are academy schools for 14–18 year olds, where STEM skills are valued highly. Students take technical courses in STEM subjects alongside a broad general education. Each UTC is sponsored by a university, sometimes in partnership with a FE college and local employers. The aim is to equip students with specialist knowledge and skills to allow them to go on to work in STEM jobs in areas including construction, engineering and IT, with the curriculum directed by employers and the university.

These schools operate longer days, typically from 8.30am until 5pm, and a longer school year of 40 weeks – extra time that is considered vital if students are to complete the curriculum. They spend more time in technical education as they get older. Employability skills are part of the curriculum and academic teaching is illustrated through the UTCs technical specialism.

Students take part in projects set by employers and universities, working both at the college and in the workplace. Younger employees of these businesses act as mentors to support the students, offering informal careers advice as well as training. By September 2013, 17 UTCs were open and the Government has pledged to open 20 more each year.

BOX 4

Studio Schools[57]

Studio Schools are small schools of around 300 students for 14–19 year olds with year-round opening and a 9am–5pm working day.

Students follow the National Curriculum, take academic and vocational qualifications, with the curriculum designed to give them employability and life skills as well as paid work placements linked directly to employment opportunities in the local area.

Students are assigned a personal coach, with whom they meet once a fortnight to develop their own personalised learning plan and track their progress. They learn through enquiry-based learning, by completing enterprise projects in school, local businesses and the community. Students in Year 10 and Year 11 (aged 14–16) participate in work experience each week.

The first Studio School opened in 2010 and the Studio Schools Trust, an organisation set up to link them together, aims to establish a large network across Britain.

56 Tomlinson, M 2014 *The philosophy and structure of the curriculum in university technical colleges*. *School Sci. Rev*. **352**, 37–42.

57 See http://www.studioschoolstrust.org/what-studio-school, accessed 16 April 2014.

91%

agree that young people's interest in science is essential for our future prosperity.

2014 Public attitudes to science 2014. Main report. London: Ipsos Mori Social Research Institute.

Adding to the evidence for a broader curriculum up to 18, research for this report conducted by the Institute of Education (IOE) has shown that the study of some form of English from ages 16 to 18 would be beneficial, for instance in honing essential literacy and employability skills. The IOE suggests that a combination of literacy, communicative, mathematical and scientific abilities is key to successful participation in pluralist, democratic societies, which 'increasingly rest on the assumption that their populations have access to information in a variety of modes, and are able to use it to inform judgement within work and community settings'.[58]

New educational frameworks are needed in order to correct these imbalances and ensure that the UK's education systems are capable of preparing young people both for areas of study that do not yet exist, for example in new areas of science still to be discovered, and for jobs which have not yet been created.

While establishing the precise detailed composition of these baccalaureate frameworks requires an in-depth consideration that is beyond the scope of this report, evidence – in part from international education systems – suggests their defining features should include:

(i) a seamless educational provision for all young people aged 5–18;

(ii) enabling students to pursue a blend of academic and vocational courses of an equally high quality and to transfer between these forms of learning; and

(iii) ensuring that students receive a truly rich and rounded education in a broad range of subjects through to age 18.

These new frameworks should enable all young people to study mathematics and science in some form to age 18, as is discussed below, also fully recognising the value of subjects in the arts, humanities and social sciences.

However, it is important to acknowledge at this point two major challenges to these new frameworks. The first challenge is the continuing shortage of appropriately qualified science and mathematics teachers. More will certainly be required to ensure inspirational science and mathematics teaching and learning post-16. This will require a significant shift and a strategy based on providing more flexible routes into initial teacher education, up-skilling and retraining, which are discussed in part five.

The second challenge is the effect that new educational frameworks would have on the length and composition of the typical school/college day and week. This is already being addressed as shown in Box 3, where UTCs have changed the timeframes of the school/college years.

58 Tolmie, A, Creese, B, Nelson, R, Block, J, Swain, J, Cara, O, Earley, P, Glauert, E, Harrison, M, Hoyles, C, Johnson, S, Levinson, R, Pratt, D & Reiss, M 2013 Report on leadership and workforce issues within UK Science and Mathematics Education. Report for the Royal Society. (Hereon referenced as Ev. 8, as in Appendix 7.2, published online at www.royalsociety.org/vision)

3.2 Mathematics education to age 18

It seems evident from the latest scientific and technological advances that the landscape of 2030 will require people to be highly adept at analysing and handling data, including strong skills in computational thinking (problem-solving using computer science techniques).

Yet the notion that it is acceptable to be mathematically illiterate is deeply ingrained in British culture.[59] In allowing young people to drop mathematics at 16, education systems play to this cultural weakness.[60] Engaging with mathematics for longer should increase people's mathematical confidence, which will in turn support a long-term cultural change. Mathematics has been demonstrated to be one of the best ways to improve logical skills, and for this to happen, students should encounter mathematics beyond GCSE and equivalent qualifications.[61] The study of science backed with solid mathematical content also helps develop such skills.

The principle that mathematics should be studied from the start of school until the age of 18 is now accepted by Governments around the world,[62] but is yet to be established across the whole of the UK. Only 13% of young people in the UK study mathematics beyond 16, and it has been estimated that at least one in four economically active adults is functionally innumerate.[63] Too many young people leave compulsory education having not achieved a grade C or above in GCSE mathematics. Too few go on to study mathematics at A-level (just 20% of students who achieve a grade C or above in GCSE mathematics go on to gain AS or A-level qualifications in the subject).[64] In Scotland, low levels of literacy and numeracy have been recorded, with 65% of men and 77% of women experiencing difficulties with numeracy.[65] In Wales, too, a lack of basic numeracy affects more than half of its working-age population.[66]

13%

of young people in the UK study mathematics beyond age 16.

59 See, for example, http://www.nationalnumeracy.org.uk/why-are-attitudes-important/index.html, accessed 13 May 2014.

60 OECD 2013 Mathematics self-belief and participation in mathematics-related activities. In *PISA 2012 results: ready to learn – students' engagement, drive and self-beliefs (vol. III)*, pp. 79–104. Paris: OECD Publishing.

61 Attridge, N & Inglis, M 2013 Advanced mathematical study and the development of conditional reasoning skills. *PLoS ONE* **8**, e69399. (See http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0069399, accessed 12 May 2014.)

62 Hodgen, J, Pepper, D, Sturman, L & Ruddock, G 2010 *Is the UK an outlier? An international comparison of upper secondary mathematics education*. London: Nuffield Foundation.

63 Vorderman, C, Budd, C, Dunne, R, Hart, M & Porkess, R 2011 *A world-class mathematics education for all our young people*. (See http://www.tsm-resources.com/pdf/VordermanMathsReport.pdf, accessed 28 April 2014.)

64 Department for Education 2013 *Introduction of 16 to 18 core maths qualifications. Policy Statement*. (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/266717/Policy_statement_on_16-18_Core_Maths_qualifications_-_final__3_.pdf, accessed 28 April 2014.)

65 Scottish Government 2008 *New light on adult literacy and numeracy in Scotland. Summary report*. Edinburgh: Scottish Government. (See http://www.scotland.gov.uk/Resource/Doc/216990/0058169.pdf, accessed 28 April 2014.)

66 Equality and Human Rights Commission 2011 *How fair is Wales?* (See http://www.equalityhumanrights.com/uploaded_files/Wales/how_fair_is_wales.pdf, accessed 8 May 2014.)

Physics-based industries contribute

£77 billion

of Gross Value Added to the economy

However, more jobs now require better levels of management expertise and problem-solving skills, many of which are mathematical in nature. Mathematical skills gained at school can have a direct effect on earnings, adding a premium of up to 10%.[67] High-level mathematical competency can also contribute to national economic health. In 2010 the mathematical science research base accounted for 2.8 million jobs and £208 billion in terms of Gross Value Added (GVA). This is equivalent to around 10% of the UK workforce and 16% of total UK GVA.[68]

A major stumbling block to increasing post-16 participation in mathematics is that there are few or no mathematics courses available for those who do not pursue a specialist mathematics path after compulsory schooling.[69] In England this problem is being addressed through the development of new post-16 mathematics qualifications designed to cater for young people who do not necessarily wish to specialise in mathematics (but could potentially subsequently study for an A-level in the subject) and the needs of employers.[70] New qualifications are also currently in development in Scotland to support the Curriculum for Excellence (CfE), which introduced a new way of learning to schools and colleges in 2010.

3.3 Science education to age 18

Given the importance of science, engineering and technology to the economy, the value of STEM qualifications to the individual[71] and employers' demand for these,[72] an educational framework requiring all young people to study science to age 18 could potentially also reap great benefits.

Similarly to mathematics, science adds great value to the economy. For example, each worker in physics-based businesses contributes twice the national average of GVA to the economy and the industry directly contributes £77 billion. If indirect effects are taken into account, this figure increases to £220 billion.[73]

Physics and mathematics are crucial subjects for engineering, which as figure 1 shows, is a major source of employment and wealth in the UK economy. Current forecasts show that the demand for graduate engineers exceeds supply and that it is pervasive across all sectors of the economy. Taking into account growth in employment opportunities and the need to replace people leaving the labour market, for example, due to retirement, figures show that by 2020, the UK needs 830,000 STEM professionals at degree level and 450,000 STEM technicians (at Levels 3 and 4).

67 Walker, I & Zhu, Y 2013 *The benefit of STEM skills to individuals, society and the economy. A report for the Royal Society*. (Hereon referenced as Ev. 9, as in Appendix 7.2, published online at www.royalsociety.org/vision)

68 Deloitte 2012 *Measuring the economic benefits of mathematical science research in the UK. Final report*. (See http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/DeloitteMeasuringTheEconomicsBenefitsOfMathematicalScienceResearchUKNov2012.pdf, accessed 8 May 2014.)

69 Hodgen, J & Marks, R 2013 *The employment equation: why our young people need more maths for today's jobs. Report for the Sutton Trust*. (See http://www.suttontrust.com/news/publications/the-employment-equation-why-our-young-people-need-more-maths/, accessed 8 May 2014.)

70 *Op. cit.*, note 64.

71 Ev. 9.

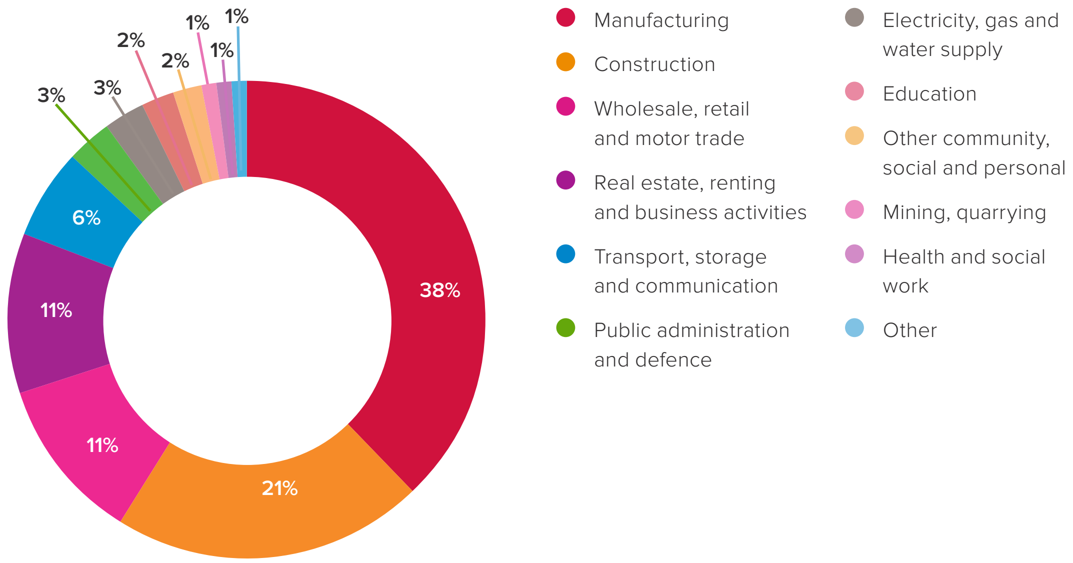
72 *Op. cit.*, note 1.

73 Institute of Physics 2012 *The importance of physics to the UK economy. A report prepared for the Institute of Physics by Deloitte*. London: IoP.

FIGURE 1

Engineers in the UK workforce

Engineers contribute a sizeable proportion of the UK's workforce –
2.42 million out of a total of 27.37 million people.



Source: Labour Force Survey Data. Analysis undertaken by The Royal Academy of Engineering. September 2013.

Yet despite this opportunity, there are still not enough young people progressing to post-16 STEM qualifications. The UK faces a shortfall of 40,000 graduates every year as well as many shortages in jobs typically associated with technical and vocational education in sectors as diverse as glass, plastics, agriculture and food processing.[74,75]

Research suggests that it is too often only children from more affluent homes who choose to continue studying science and mathematics post-16 or those from homes with medium or high 'science capital' (ie those with close family or friends with science-related qualifications, understanding, knowledge or interest in science and technology).[76,77] This means that currently the study of science after the period of compulsory education is restricted to an elite. All children deserve the same opportunities in life, and education should be a vehicle for greater equity.

74 *Op. cit.*, note 1.

75 Lord Baker of Dorking CH 2014 *The skills mismatch*. London: Edge Foundation.

76 Homer, M, Ryder, J & Donnelly, J *Sources of differential participation rates in school science: the impact of curriculum reform*. *BERA J.* **39**, 248–265.

77 *Op. cit.*, note 44.

The study of computer science should begin from an early age.

3.3.1 Computing

Computing (encompassing digital literacy, information technology (IT) and computer science) is of enormous importance to the economy. One new area, the global cyber security market, is estimated to be worth more than £100 billion per annum[78] and the UK remains a leader in the creative economy, which accounted for 2.55 million jobs in 2012, or 1 in every 12 jobs in the UK. IT, software and computer services was the largest creative economy group, employing 791,000 people in 2012 (31% of employment in the creative economy).[79] Retaining the UK's global strengths in the high-tech and digital industries of the creative economy needs education systems that support the fusion of art and technology.[80]

Computing has a critical role as an underpinning subject in STEM and the creative subjects, but also has a transformational capacity, bringing with it new ways in which discovery and innovation can be achieved. As a rigorous academic discipline of great importance to the future of many young people, the study of computer science should begin from an early age. So it is encouraging that, in response to the joint Royal Society/ Royal Academy of Engineering report, *Shut down or restart?*, the UK Government moved to embed computing within England's National Curriculum from primary education through to age 16, with a new programme of study due to be introduced from September 2014.[81]

It is to be hoped that the governments in Northern Ireland, Scotland and Wales will follow suit, with the newly created UK Forum for Computing Education (UKforCE) providing advice on computing curricula, qualifications and assessment and the supply and training of computing teachers. This last issue remains a major challenge to the ambition of ensuring all young people enjoy a rich and useful computing curriculum. New partnerships between governments and the computing industry have, however, already been forged and will provide training and resources for roughly one in every five primary school teachers in the country and at least three specialist teachers in every secondary school.[82]

3.3.2 Design and technology

Engineering skills are needed throughout the economy, in professional services, energy, transport, communications and construction, as well as in manufacturing. These skills take a long time to develop, as they result predominantly from the study of mathematics and science in school. Like law or economics, engineering is not a core school subject. Physics and mathematics are the basis for studying engineering and technology, complemented by other subjects such as design and technology, computer science, chemistry and biology.

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78 UK Trade & Investment 2013 *Cyber security. The UK's approach to exports*. London: UKTI.

79 Department for Culture, Media and Sport 2014 *Creative industries economic estimates*. Statistical release, 14 January 2014. London: DCMS.

80 NESTA 2011 *Next Gen. Transforming the UK into the world's leading talent hub for the video games and visual effects industries. A review by Ian Livingstone and Alex Hope*. London: NESTA.

81 Royal Society 2012 *Shut down or restart? The way forward for computing in UK schools*. London: Royal Society.

82 With the new Computing curriculum coming into force across UK primary and secondary schools in September, Microsoft and Computing At School (CAS) are joining forces to help teachers inspire a new generation of young people. Backed by a £334,000 investment from Microsoft, CAS is holding a series of 'Back to School' training sessions to show teachers how they can take the complexity of coding and computer science and make it engaging to the touch screen generation. (See http://www.computingatschool.org.uk/index.php?id=current-news&post=microsoft-and-cas-form-ground-breaking-partnership, 8 April 2014, accessed 9 May 2014.)

People who have studied engineering are in demand to fill other occupations, as their analytical approach and project management skills are applicable in many environments. Demand for engineering skills, and the scientific and mathematical knowledge that underpins them, exists not only at the point of design and invention, but all the way through the supply chain. As the Perkins review acknowledged, John Logie Baird's television, Frank Whittle's jet engine or James Dyson's vacuum cleaners 'would never have become part of people's everyday lives had it not been for the engineering skills of tens of thousands of employees who helped turn their ideas into products'.[83]

Design and technology (D&T) is likely therefore to become increasingly important within National Curricula. D&T covers such diverse areas as product design, food technology, engineering, systems and control, electronics, textiles and graphics. It involves subject knowledge as well as learning from other subjects. Since it is also oriented towards finding creative solutions to real problems, D&T examines people's needs, desires and values and encourages people to be resourceful, innovative and enterprising.

D&T is highly relevant to the future world of work, which will call on young people to apply a broad range of subject knowledge to design and manufacture. As with mathematics and science, there will be a need for more D&T teachers, and for an extensive professional development programme to run to allow existing teachers to improve their skills. This work has already started, with the launch of a new Skills Programme by the Design and Technology Association.[84]

3.3.3 Post-16 science

As with the current development of post-16 mathematics courses in England, a range of respected qualifications should be offered in science to cater for varied interests and abilities. These should not just be A-level (or their equivalent) style courses, but a menu of choices to meet the status and needs of different groups of students. Science subjects (including mainstream biology, chemistry and physics, computing and D&T) would be part of this menu, but new options would have to be developed to meet the needs of, for example, students preparing for university entrance in non-STEM subjects, and those embarking on vocational courses. Notably, in the province of Ontario, Canada, students already have a choice of science and mathematics courses designed for those who want to pursue a vocational or technical career, as well as for those completing academic study (Box 5).

Table 2 summarises some possible starting points for future models, but further work is needed to develop these new qualifications.

Nevertheless, the development of post-16 science and mathematics education is a principle that should apply just as much to a young person pursuing a full-time vocationally related course in fashion, media or business as to a student whose current programme covers A-levels or Scottish Highers in the humanities, languages or non-quantitative social sciences.

83 Department for Business, Innovation and Skills 2013 *Professor John Perkins' review of engineering skills*. London: DBIS.

84 See https://www.data.org.uk/for-partners/skills-gap-programme/, accessed 30 April 2014.

TABLE 2

Possible options for post-16 science

Post-16 group	Possible options	Current equivalent examples
University-bound to study STEM	Specialist pre-university science courses – Level 3	A-level sciences
University-bound to study non-STEM	Shorter specialist science courses – Level 3 or 'Science for Citizens' courses – Level 3	AS Biology; AS Science in Society
Employment-bound, in FE college or in schools	Work-related science courses – Level 2 or 3	BTEC Science, Level 2 or 3
Apprentices	Audit of science content of apprenticeship and top-up where necessary	

However, special attention also should be paid to vocational courses and qualifications in STEM-related disciplines, including engineering, applied science, construction and computing. Many of these courses are built around large-scale qualifications with specialist modules in engineering, computing, mathematics and science and/or large amounts of embedded mathematics and science.

In developing assessment requirements for new non-A-level post-16 mathematics and science curricula and qualifications, examination boards should be asked to ensure that those are compatible with apprenticeship training patterns.

3.4 Vocational education and training

Vocational education and training is a key part of UK education – and central to meeting the demand in the future UK workforce for STEM qualified people. A majority of young people follow courses, post-16, which are entirely, broadly or partly vocational in schools and colleges across the UK. Many young people are motivated by courses that relate to the world of work, as these provide them with a clear reason for study, even if they have yet to decide on their future career. A large number of these courses are STEM-related and, as Figure 2 shows, more STEM qualifications in England are completed by 16–18 year olds in the FE and skills sector than in schools.

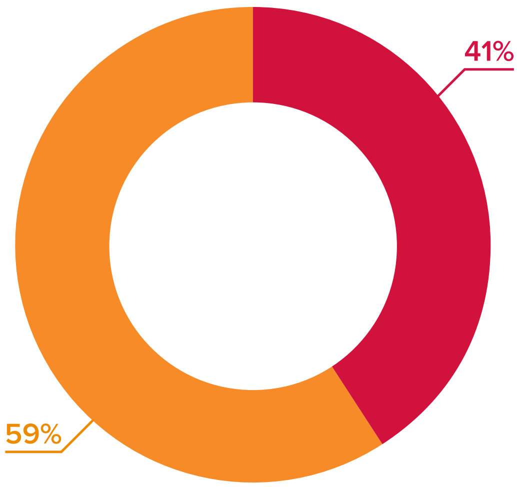
BOX 5

Different paths to science and mathematics to age 18 in Canada[85,86,87]

In the Canadian province of Ontario, teenagers aged 17 and 18 can choose from a variety of mathematics and science courses that are designed to prepare them for university, college or the workplace. Entry to university or college courses depends on having previously taken an academic course, and for the workplace stream entry depends on having previously taken a lower level academic or applied course.

Mathematics workplace preparation courses cover: earning and purchasing; saving, investing and borrowing; transportation and travel; reasoning with data; personal finance; and applications of measurement. Science workplace courses include the following topics: the human impact on the environment; human health; energy conservation; workplace chemicals in consumer products; disease prevention; electricity; and nutritional science.

FIGURE 2



Proportions of publicly funded STEM qualifications completed by 16–18 year olds in England (2010/11).

(Total no. of STEM qualifications is 500,000)

Source: Engineering UK

85 Ministry of Education Ontario 2007 *The Ontario curriculum. Grades 11 and 12. Mathematics. Revised*. Ontario, CA: Ministry of Education. (See http://www.edu.gov.on.ca/eng/curriculum/secondary/math1112currb.pdf, accessed 8 May 2014.)

86 NFER and Arad Research 2013 *A rapid evidence assessment on the impact of curriculum and assessment arrangements within high-performing countries*. Llandudno Junction: Welsh Government.

87 Ministry of Education Ontario 2008 *The Ontario curriculum. Grades 11 and 12. Science. Revised*. Ontario, CA: Ministry of Education. (See http://www.edu.gov.on.ca/eng/curriculum/secondary/2009science11_12.pdf, accessed 8 May 2014.)

The best of these courses provide a 'clear line of sight to work',[88] as vocational learners must be able to see why they are learning what they are learning, understand what the development of occupational expertise is all about, and experience the job in its context. With good teaching and skilful guidance, these courses present students with a number of options for progression and are broad enough to allow them to change path as their ideas about the future change.

The changing skills needs of the economy and the desire to boost the take-up of advanced and higher apprenticeships provide an exciting opportunity for the FE sector, which should aspire to the status enjoyed by their counterparts in Austria and Germany. Through its links with local and regional employers, the FE sector is well placed to offer a range of employer-led qualifications and could have a much larger role in the future of Higher Education in England.[89]

Despite the potential value both to the individual and to the economy at large, young people have been actively discouraged from opting for vocational education because many parents and teachers have not thought it is worthwhile.[90] The rise of tuition fees in England to attend degree courses at university and a recent policy focus in the UK to raise the importance of vocational education may help to change this situation, but challenges remain. A lack of appropriate careers advice is preventing the status of vocational learning from being raised.[91] Some teachers in 11–18 schools lack impartiality by encouraging some students to stay on in their sixth forms rather than encouraging them to look at all the options available, including vocational courses.[92]

Last year's survey by the OECD concluded that England has too little high-quality vocational provision at post-secondary level in comparison with many other countries, and relative to demand,[93] and recent reviews in Wales and Scotland (ongoing) have been critical of vocational education provision there.[94, 95, 96]

88 Learning and Skills Improvement Service 2013 *It's about work. Excellent adult vocational teaching and learning. The summary report of the Commission on Adult Vocational Teaching and Learning*. London: LSIS.

89 *Op. cit.*, note 1.

90 See http://www.edge.co.uk/news/2014/february/children-labelled-too-clever-for-vocational-education, accessed 9 May 2014.

91 *Op. cit.*, note 88.

92 Hughes, D & Gration, G 2009 *Literature review of research on the impact of careers and guidance-related interventions*. Reading: CfBT.

93 Musset, P & Field, S 2013 *A skills beyond school review of England*. OECD Reviews of Vocational Education and Training. Paris: OECD.

94 Welsh Government 2012 *Review of qualifications for 14 to 19-year-olds in Wales. Final report and recommendations*. Caerphilly: Welsh Government.

95 Wood, I 2013 Commission for developing Scotland's young workforce. Interim report. (See http://www.scotland.gov.uk/Resource/0043/00433287.pdf, accessed 14 March 2014.)

96 Teese, R, Juva, S, Kelly, F & van Damme, D 2007 *Quality and equity of schooling in Scotland*. Reviews of national policies for education. Paris: OECD.

The OECD report follows a Government review in 2011, which found that many low-level vocational qualifications have little or no labour market value, and that at least 350,000 16 – 19 year olds were receiving little or no benefit from the post-16 education system.[97]

Since then, the Government has moved to improve vocational education in various ways, including concentrating funding in educational institutions on a subset of vocational qualifications that meet its quality criteria, emphasising work experience for young people in full-time post-16 education, extending requirements for study of mathematics and English and launching a major reform of apprenticeships.[98]

Government action[99] has also committed to improving the status and professionalism of vocational teachers. The Education and Training Foundation, IOE and Association of Employment and Learning Providers (AELP) are developing Teach Too, a programme aimed at encouraging people working in industry to spend some of their time in vocational teaching, and to enable teachers to spend time in industry. These are steps in the right direction, but there is still a great deal to be done, notably with respect to STEM subjects and occupations with a strong demand for STEM skills.

3.4.1 Apprenticeships

Apprenticeships are of particular importance within the vocational context. Between 2013 and 2022, apprenticeships in England are forecast to contribute £3.4 billion of net productivity gains to the UK economy.[100] Moreover, while the average incomes of apprentices are below the average lifetime income of graduates, both figures conceal wide variation in the returns to education and training. Studies of apprentices consistently show that an apprenticeship has high wage returns, much higher than if a vocational qualification is taken in full-time education.[101, 102]

Apprenticeships currently cover over 170 industries and 1,500 job roles, in a range of sectors from marketing to accountancy, engineering to veterinary nursing, community arts to construction. There are currently three levels: intermediate, advanced, and higher. Apprenticeships in general are highly oversubscribed, and this is especially true of the best STEM apprenticeship programmes, such as those provided by BAE Systems, BT or Rolls–Royce.

Between 2013 and 2022, apprenticeships in England are forecast to contribute

£3.4 billion

of net productivity gains to the UK economy.

97 Wolf, A 2011 *Review of vocational education – the Wolf report*. (See http://dera.ioe.ac.uk/11621/1/DFE-00031-2011.pdf, accessed 9 May 2014.)

98 Richard, D 2012 *The Richard review of apprenticeships*. (See http://www.schoolforstartups.co.uk/richard-review/richard-review-full.pdf, accessed 9 May 2014.) See also subsequent Government consultation documents.

99 Department for Education 2013 *Wolf recommendations progress report*. London: DFE.

100 Centre for Economics and Business Research 2013 *Productivity matters: the impact of apprenticeships on the UK economy*. London: CEBR.

101 McIntosh, S 2004 *The returns to apprenticeship training*. CEP DP 622. London: Centre for Economic Performance, LSE.

102 McIntosh, S 2007 *A cost–benefit analysis of apprenticeships and other vocational qualifications*. RR 834. Sheffield: DfES.

There is still, however, much that needs to be done to ensure that the value of apprenticeships is recognised. The latest Global Talent Shortage survey showed that the top two shortages for jobs worldwide were for skilled trade workers and engineers.[103] Yet in the UK currently 11 per 1,000 students undertake an engineering apprenticeship, whereas European competitors such as France (17 per 1,000) or Germany (40 per 1,000) have significantly more.[104]

Apprentices are not students: they are employees drawing a wage. Current reforms will return English apprenticeships to a form much closer to the modal European pattern, in which the main architects of apprenticeship training are employers. However, employers cannot, on their own, be expected to re-design apprenticeship standards while also assuring these standards provide the broad occupational competence Government has rightly identified as necessary. To achieve this, employers will need to be supported, including by professional bodies, as the guardians of occupations and professional standards.

It is of critical importance to the quality of apprenticeships and the future development of the UK that training programmes include substantial requirements for general skills including, notably, mathematics and English. Government should ensure that all apprentices receive a strong element of general education in their training, to allow them to take on new roles and to adjust to changing working practices and new technologies as they arise; and in particular, given the central importance of mathematics in skill shortage areas, that the minimum mathematics requirements for different levels of apprenticeship be progressively increased from their current low levels.

In many sectors, professional bodies will be able to ensure apprenticeships are both relevant to employers and provide the broad, occupational competence that Government wants. In STEM, this occupational competence is guaranteed by professional registration schemes such as Registered Engineering Technician and Registered Science Technician. Similar schemes also exist, or are under development, in accountancy and IT. The UK Government's current reform programme for apprenticeships, while putting employers in the driving seat, recognises the important role that professional registration can play in quality-assuring apprenticeships. In future, all publicly funded apprenticeships will be required to meet professional registration requirements in sectors where these exist.[105] In this way, completing apprentices will be able to secure post-nominal letters such as EngTech or RSciTech, just as graduates use BEng or BSc.

These developments are extremely welcome and indeed exemplify the important role for the professional bodies in the Vision, described further in parts four and five. In the past, the STEM professional bodies (such as the Royal Society of Chemistry, the Institution of Mechanical Engineers, etc) played a major role in the development of vocational qualifications, particularly at technician level. This engagement brought additional status to the best vocational qualifications and ensured access to the highest levels of the science and engineering professions via a vocational route. Although the link between professional bodies and technician-level qualifications weakened during the 1990s and 2000s (in part due to the rapid expansion of Higher Education), it is now receiving significant attention. Many professional

103 Manpower Group 2013 *2013 talent shortage survey*. Research results. Uxbridge: ManpowerGroup.

104 *Op. cit.*, note 22.

105 Department for Business, Innovation and Skills 2013 *The future of apprenticeships in England: implementation plan*. BIS/13/1175. London: DBIS.

bodies are looking to re-establish a robust vocational pathway in the STEM sectors, using professional registration as the framework to do so. In this way, a registered technician will be able to see clearly how s/he might progress over time to become a chartered engineer, scientist, IT professional or accountant.

3.5 Essentials of science and mathematics education

The following strategies are essential in supporting high-quality science and mathematics provision in both primary and secondary schools and FE colleges.

3.5.1 Practical work and problem-solving

Practical work is integral to science, underpinning skills development and procedural knowledge and understanding, that are central to the appeal and effectiveness of science education.[106] As the Council of Science and Technology (CST) has said: "Experiments are the essence of science, and studying science without practical experimental work is like studying literature without reading books".[107]

Practical work demonstrates the empirical nature of science, and its crucial value is in helping explain phenomena observed in the natural world. It should not, therefore, be considered an 'additional component' of teaching and learning.[108] Instead, throughout their schooling, young people should take part frequently in classroom and outdoor scientific activities in which they observe or manipulate real objects and materials. Provision for disabled or dyslexic students should also be considered, so that all students can benefit from practical learning.

Students report they are more engaged and positive about science when stimulated by investigative work, and it has been shown that exciting practical work increases their interest in science-related careers and helps bring home to them the relevance of what they are studying.[109]

Moreover, practical skills are highly valued by employers, with more than 70% of STEM employers in the UK recruiting school leavers to positions requiring practical skills.[110] Countries such as Canada, Singapore, the Netherlands, Japan and Finland, which are high-ranking in international league tables of performance in science, emphasise experiment and observation in the curriculum.[111]

"Experiments are the essence of science, and studying science without practical experimental work is like studying literature without reading books."

Council for Science and Technology 2013 Letter to Michael Gove on how best to educate future scientists and engineers, 31 July 2013.

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106 Abrahams, I, Reiss, M J & Sharpe, R M 2013 *The assessment of practical work in school science*. *Studies Sci. Educ.* **49**, 209–251.

107 Council for Science and Technology 2013 Letter to Michael Gove on how best to education future scientists and engineers, 31 July 2013. (See https://www.gov.uk/government/organisations/council-for-science-and-technology, accessed on 13 November 2013.)

108 Science Community Representing Education 2014 *SCORE principles: the assessment of practical work*. (See http://www.score-education.org/media/14286/score%20principles%20for%20the%20assessment%20of%20practical%20work%202014.pdf, accessed 9 May 2014.)

109 Ev. 3.

110 Gatsby Charitable Foundation 2011 *Employers' views on science skills for the workplace*. Research briefing. (See http://www.gatsby.org.uk/~/media/Files/Education/Practical%20work%20research%20summary%203%20STEM%20employers%20views%20on%20science%20skills%20181012.ashx, accessed 9 May 2014.)

111 Ev. 2.

In 2011

57%

of university science staff reported that practical skills of new undergraduates had declined in the previous five years.

There should be a move to reverse the recent reduced emphasis on practical work across the UK.[112, 113] In 2011, 57% of university science staff reported that practical skills of new undergraduates had declined in the previous five years.[114]

One major challenge to increasing practical science in schools is a dearth of qualified technicians. Although there are no accurate up-to-date disaggregated data on the numbers of science technicians in UK schools and colleges, the indications are that the shortfall of 4,000 technicians identified by the Royal Society and the Association for Science Education (ASE) back in 2002 has not been rectified.[115] A recent Science Community Representing Education (SCORE) report indicated that over a quarter of survey respondents in state-funded schools had inadequate technician support and that retention is weak because of poor working conditions.[116]

For many years, most technicians have been poorly paid, and hired on insecure short-term contracts, that reduce their scope for career development. They have proven hard to replace, particularly with regard to physics specialists.[117] The Gatsby Charitable Foundation found in its recent survey of science teachers that a quarter had scaled back the amount of practical work in their courses owing to changes in the curriculum, assessment priorities, budgets and lack of technician support.[118] Schools are likely to find that they are in an increasingly competitive market for technicians.[119] There is an urgent need for a long-term strategy to assure sufficient supply and retention of technicians in the UK's schools and colleges, for instance through apprenticeships.

A further, well-documented challenge is the lack of well-resourced laboratories and outdoor spaces available to schools. In 2013, two reports were published which found that shortages of basic equipment and consumables meant that many primary and secondary schools are unable to teach practical science effectively.[120, 121]

112 Science Community Representing Education 2008 *Practical work in science: a report and proposal for a strategic framework*. London: SCORE.

113 Gatsby Charitable Foundation 2012 *School teachers' views and experiences of practical work in science. Results of research undertaken by EdComs for the Gatsby Charitable Foundation, February 2012*. Research briefing. (See http://www.gatsby.org.uk/~/media/Files/Education/Practical%20work%20research%20summary%202%20Teacher%20views%20of%20practical%20work%20181012.ashx, accessed 2 June 2014.)

114 Gatsby Charitable Foundation 2011 *University teachers' views on the practical skills of science undergraduates. Results of research undertaken by Laura Grant Associates for the Gatsby Charitable Foundation*. Research briefing. (See http://www.gatsby.org.uk/~/media/Files/Education/Practical%20work%20research%20summary%201%20Practical%20skills%20of%20science%20undergraduates%20181012.ashx, accessed 2 June 2014)

115 Smithers, A & Robinson, P 2013 *The science and mathematics teaching workforce*. A report to the Royal Society. (Hereon referenced as Ev. 7, as in Appendix 7.2, published at online at www.royalsociety.org/vision.)

116 Science Community Representing Education 2013 *Resourcing practical science at secondary level*. London: SCORE.

117 *Ibid*.

118 *Op. cit.*, note 113.

119 *Op. cit.*, note 10.

120 SCORE 2013 *Resourcing practical science in primary schools*. Report. (See http://www.score-education.org/policy/curriculum/practical-work-in-science, accessed 9 May 2014.)

121 SCORE 2013 *Resourcing practical science in secondary schools*. Report. (See http://www.score-education.org/policy/curriculum/practical-work-in-science, accessed 9 May 2014.)

Learning in mathematics is deeper and more enjoyable when pupils are actively involved in their learning. They solve a range of problems, often in groups or pairs, and see problem-solving, in part at least, as a social activity. They apply mathematics to problems in the real world, including in areas such as personal finance, investment and mortgages. They explore reason and prove in algebra and geometry, using their mathematical skills in a range of subjects. They handle real data including those met in other subjects and explore probability practically as well as theoretically. Ofsted found such a rich curriculum was comparatively rare, but that it was highly effective when in place.[122]

3.5.2 Interdisciplinary learning

Although it will remain important for the disciplines of mathematics, physics, chemistry, biology, computing and D&T to be taught separately in schools and colleges, in order to ensure students acquire comprehensive knowledge, skills and understanding in these, developments in science and technology usually happen through collaboration and open, dynamic dialogue within and across disciplines.

Therefore, as technologies converge and the world outside school increasingly demands cross-disciplinary skills, science and mathematics education should change to reflect the nature of scientific enquiry and technological innovation as it is conducted in industry, universities and research centres across the world (Box 6).[123]

BOX 6

The importance of cross-disciplinary skills

The trend in converging technologies and cross-disciplinary skills is particularly important to the UK with its strong dependence on sectors like the life sciences.

Bioinformatics is an example of a rapidly growing interdisciplinary scientific field that derives knowledge from computer analysis of biological data, using techniques and concepts drawn from informatics, statistics, mathematics, chemistry, biochemistry, physics and linguistics. The global market for its products and services is forecast to see double-digit annual rates of growth.

Source: The Future of Work. Jobs and Skills in 2030, UK Commission for Employment and Skills.

Science and mathematics education needs to reflect the nature of scientific enquiry and technological innovation as it is conducted.

122 Ofsted 2012 *Made to measure. Messages from inspection evidence*. Ref. no. 110159. London: Ofsted.

123 Reynolds, D & Kelly, A 2013 *Accountability and the meaning of 'success' in education systems and STEM subjects*. A report for the Royal Society. (Hereon referenced as Ev. 1, as in Appendix 7.2, published online at www.royalsociety.org/vision)

> **“The way to crack the big problems is not to use ideas from a single discipline, but to integrate modes of thinking from across disciplines.”**
>
> Marcus du Sautoy[124]

Indeed, the Royal Society of Edinburgh notes that at school level, interdisciplinary learning (IDL) in STEM subjects:

‘creates and develops **awareness of wider career opportunities** and stimulates **curiosity and motivation**, while emphasising the inter-relationships of phenomena [and that it] promotes **higher-order thinking skills** such as creativity, critical and systems thinking, synthesis, evaluation and analysis, and is commonly associated with diverse types of learning such as **co-operative, inquiry-based and contextual learning**… In implementing problem-based IDL, teachers become facilitators, supporting pupils to become self-directed learners.’[125]

Additionally, IDL can:

- through its application to practical problems, give young people a better idea of what ‘real’ scientists do, and stimulate their interest in and attitudes towards science and mathematics;[126]
- improve attainment (eg evidence has suggested that infusing a technology curriculum with mathematics improves attainment in mathematics);[127]
- facilitate development of sought-after skills for employment, including teamwork, collaboration and the ability to ‘make connections’ between different areas of knowledge; and
- encourage cross-departmental working between school or college departments.

Science and mathematics education in the UK should broaden to reflect the reality of innovation in science and technology. IDL has already been built into Scotland’s Curriculum for Excellence,[128] thereby ensuring that the relationships between scientific disciplines are recognised alongside single-subject teaching.

124 du Sautoy, M 2013 No more isolation. *Oxford Today*, April 2013. (See http://www.oxfordtoday.ox.ac.uk/features/no-more-isolation, accessed 1 May 2014.)

125 Graham, C, Williams, G & Bryce, S 2014 Pillars and lintels: the what’s, why’s and how’s of interdisciplinary learning in STEM education. (See http://www.royalsoced.org.uk/cms/files/education/Learned%20Societies%20Science%20Education/pillars_and_lintels.pdf, accessed 25 April 2014.) Emphasis is as in the original.

126 Howes, A, Kaneva, D, Swanson, D & Williams, J 2013 Re-envisioning STEM education: curriculum, assessment and integrated, interdisciplinary studies. A report for the Royal Society. (Hereon referenced as Ev. 2, as in Appendix 7.2, published online at www.royalsociety.org/vision)

127 Ev. 2.

128 Education Scotland 2012 *CfE briefing. Interdisciplinary learning*. (See http://www.educationscotland.gov.uk/Images/IDLBriefing_tcm4-732285.pdf, accessed 1 May 2015.)

3.5.3 New technology to transform science and mathematics education

Twenty-first century technologies are changing attitudes, behaviours and the way people live and work. Massive Open Online Courses (MOOCs) and initiatives such as the Khan Academy (Box 7) are providing people of all ages with the opportunity to learn or refresh knowledge and understanding of myriad subjects, and to do so at any time of day or night.

Children are connoisseurs of technology, familiar with using computers and other digital devices from a young age and adept at performing complex tasks that enable them to play games, learn or interact with others online. But there has been little sign these talents are being used, or developed, at school.[129]

Despite this, research for this project has shown that digital technologies have the potential to transform the way the curriculum is implemented.[130] Table 3 gives some idea of the tremendous range of software currently available for use in science and mathematics education. Through these sorts of digital technologies, students and teachers are able to connect, share, analyse, assess, apply and personalise tasks.[131] Software on mobile devices allows teachers to assess students' practical work and support them as they conduct their investigations and students to record observations during experiments.[132]

Digital technologies can enable a much more personalised approach to suit the requirements of individual students. These technologies will be used for collaboration and knowledge creation rather than, as now, to 'layer technology on top of traditional teaching and learning'.[134] Future developments in primary and secondary education envisage increasing permeability between formal and informal learning, with schools opening up and taking on a role that extends beyond transmitting knowledge to 'co-constructing knowledge, creating knowledge, developing skills'.[135]

There is a strong expectation, therefore, that the new digital technologies will have a profound impact on young people's education. New learning partnerships will emerge between and among students and teachers in tasks designed to encourage deep learning when digital tools and resources become pervasive.

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129 Technology Enhanced Learning Research programme 2012 *System upgrade. Realising the vision for UK education*. London: London Knowledge Lab. (See http://tel.ioe.ac.uk/wp-content/uploads/2012/06/TELreport.pdf, accessed 9 May 2014.)

130 Ev. 6.

131 *Ibid*.

132 *Ibid*.

133 See https://dl.dropboxusercontent.com/u/33330500/KAPressFactPack.pdf, accessed 14 May 2014.

134 Fullan, M & Langworthy, M 2014 *A rich seam. How new pedagogies find deep learning*. London: Pearson.

135 Aceto, S, Borotis, S, Devine, J & Fischer, T 2014 *Mapping and analysing prospective technologies for learning. Results from a consultation with European stakeholders and roadmaps for policy action*. Report EUR 26519 EN. Seville: European Commission Joint Research Centre.

Digital technologies can enable a much more personalised approach to suit the requirements of individual students.

BOX 7

Online tuition attracts millions

The Khan Academy is a not-for-profit organisation established in 2008 by Salman Khan that aims to provide 'a free, world class education for anyone, everywhere'. According to data recently published by the Academy, its website contains a library of over 5,500 instructional videos and 100,000 practice problems covering sciences, humanities and arts subjects. It attracts over 10 million unique users a month across 200 countries and has some 350,000 registered teachers.

Those who use the academy learn at their own pace through studying using the online resources, taking assessments and earning badges and points along the way. It is also used by teachers to improve their teaching, and to enable them to monitor their students' progress or assess the performance of a whole class.[133]

3.5.4 Informal learning and the role of parents

Informal learning should become an inherent part of the science and mathematics curriculum. This may include visits to museums or botanic gardens, visits to/from STEM employers, after-school clubs and talks from role models. These are known to stimulate young people's interest in science and engineering and widen their awareness and understanding of science and mathematics.[136, 137]

The UK is fortunate in its provision of well-established and well-regarded informal learning initiatives in STEM, from the award-winning TfI initiative (Box 8) to the STEM Ambassadors, the national network of 25,000 volunteers from across higher education and industry that has, through an independent evaluation, been credited by teachers and students with achieving:

- 'increased engagement and interest in STEM subjects (reported by 86% of teachers);
- increased knowledge and understanding of STEM subjects/concepts/topics (reported by 83% of teachers);
- increased awareness of the STEM employment and career options available (reported by 67% of teachers); and
- increased awareness of the STEM study options available (reported by 62% of teachers).'[138]

136 Wellcome Trust 2012 *Analysing the UK science education community: the contribution of informal providers*. London: Wellcome Trust.

137 Wellcome Trust 2012 *Science beyond the classroom. Review of informal science learning*. London: Wellcome Trust.

138 National Foundation for Educational Research 2011 *An evaluation of the impact of STEMNET's services on pupils and teachers*. Slough: NFER.

TABLE 3

Examples of types of science and mathematics learning enhanced through digital technologies

Modes of learning facilitated by digital technologies
Modelling using design and production tools, eg touch-screen manipulation of curves in the graphical representations of formulae.
Exploring and experimenting with simulations, enabling students to explore risky behaviours and encouraging them to test their own hypotheses, asking 'What if?' questions, exploring different outcomes and reflecting on feedback to improve those outcomes in relation to a goal.
Experiential learning through mixed reality technology, enabling exploration and 'experiencing' of science concepts.
Inquiry learning with hand-held data gathering and analysis tools, enabling ways to support data gathering and manipulation and scientific inquiry activities in the field.
Collaboration through communication and productive technologies, enabling teacher-guided group work and peer-feedback in virtual learning environments.
Problem-solving with game-based learning, which has a particular role in developing mathematical thinking.
Adaptive support, which enables interactive learning within a digital environment that can be monitored or interpreted.
Online resources for self-study, enabling remote learning and tuition independent of time and place.
Generic learning technologies.

Source: Ev. 6.

BOX 8

Bringing industry into schools

Teachers from Industry (TfI) is a service through which STEM industry experts deliver workshops to primary schools in England, Scotland and Wales. TfI gives children access to a visiting STEM expert, specialist lessons, quality equipment and a fun hands-on experience. Workshops are practical, focusing on science and design and technology and are designed to enhance the formal science curriculum. They are also fast-paced whilst being inclusive, supporting all children within the classroom including special needs. After a Forces and Motion workshop for Key Stage 1, one teacher observed that children were 'enthralled by a 'fit with forces' song…it even stimulated their thoughts when doing something as simple as opening a drawer'.

Parents have a tremendous responsibility in stimulating their children's learning and encouraging their aspirations. Yet a recent survey of 460 young people aged 14 – 18 showed that more than two in five observe that their parents are uninterested in science.[139] Parents should be encouraged to share with their children's teachers the responsibility for providing such stimulating experiences, with financial support provided to ensure children from lower income families do not miss out.

There is a strong relationship between the aspiration of parents for their children and those of the children themselves. Parents with fewer financial resources tend to hold lower aspirations for their children, and young people from socially disadvantaged backgrounds tend to have lower aspirations than their more advantaged peers.[140] The experiences of parents in York (Box 9) show it is possible for these perceptions to change.

The Wellcome Trust and the US National Science Foundation launched, in April 2014, a joint research programme, Science Learning +,[141] which intends to find out more about the impact of informal science learning, how it can be measured and how it can better reach people from under-served communities.

BOX 9

Helping parents become engaged in their children's science lessons

Science is for Parents Too is a free course run by the University of York with support from the Wellcome Trust in order to help parents and carers of primary aged children understand the science taught in schools, create resources for use at home and raise parents' aspirations. The course is practical – parents participate in demonstrations and experiments as well as trips to see science in action. The course is not assessed: it is designed to be fun and informal.

An independent evaluation in 2013 found that attendees on the course felt more confident about helping their children with science homework, with some being more motivated to visit science museums. Further, children of parents who had attended the course were observed to have more positive attitudes towards science – and increased scientific knowledge as a result of undertaking experiments at home – compared with a control group of children whose parents were not participating in the course.[142]

139 Wellcome Trust Monitor 2012 Wave 2, core data tables, table 217. (See http://www.wellcome.ac.uk/About-us/Publications/Reports/Public-engagement/WTX058859.htm, accessed 9 May 2014.)

140 Gutman, L M & Akerman, R 2008 *Determinants of aspirations*. Research brief DCSF-WBL-03-08, June 2008. London: DCSF.

141 Wellcome Trust 2014 *Science Learning+: exploring the impact of informal science learning*, 10 April 2014. (See http://www.wellcome.ac.uk/News/Media-office/Press-releases/2014/WTP056218.htm, accessed 9 May 2014.)

142 West, S 2013 *Evaluation of Science is for Parents Too* course. Stockholm Environment Institute. (See https://www.york.ac.uk/media/sei/documents/publications/Evaluation_of_Science_is_for_Parents_Too.pdf, accessed 9 May 2014.)

3.5.5 Prospective impact of neuroscience and psychological research on learning

A review of current knowledge from neuroscience and psychology undertaken for this report concludes growing, but cautious, optimism among neuroscientists and psychologists that their developing understanding of the brain and behaviour could have an impact on educational practice.[143]

This review demonstrates the extent to which cognitive processes in the brain are understood to affect behaviour, attitudes towards and performance in STEM subjects, and that effective pedagogical strategies exist to provide learning experiences that best meet the needs of learners. These strategies include structuring lessons to space out periods of learning rather than doing everything at once, and using visual and auditory content, worked examples and testing to improve learning and retention. In addition, it appears that exercise may also enhance academic performance.

Connections with other fields of inquiry are being made. These include understanding how attitudes towards subjects are influenced by an individual's ability to concentrate, reason and resist impulses and achievement in STEM subjects; and how understanding of cognitive function may influence the development or usage of new digital technologies. For instance, as indicated in § 3.5.3, adaptive tutoring technologies enable a more personalised education in school or at home and neurofeedback technologies provide individuals with feedback about their brain activity that, duly interpreted, will help improve their performance.

It appears, then, that knowing more about brain development during childhood and adolescence (*viz*. § 2.2) might help teachers to decide better 'when to teach what'.[144] However, although findings from neuroscience research may have the potential to help teachers, there is not yet enough evidence about the impact of this science.

The Wellcome Trust and the Education Endowment Foundation (EEF) have launched a £6 million fund to pay for collaborations between teachers and neuroscientists, in order that the impact of neuroscience on teaching can be evaluated. But despite the lack of evidence, and notwithstanding that there are ethical considerations over certain types of intervention, there is clearly support among parents and teachers for interventions based on neuroscience to be developed and implemented in schools.[145, 146]

With neuroscience and psychology reaching new frontiers, strategies should be tested and, where effective, be taught to trainee teachers. In addition, the risk of adopting practices based on 'neuromyths' should be communicated to teachers and parents. For example, learning styles and the idea that 'brain power' is affected by a 'dominant' side of the brain have weak, if not opposing, evidence for their effectiveness in children's learning.[147]

143 Howard-Jones, P & Jay, T 2013 *What are the implications of psychology and neuroscience research for STEM teaching and learning?* A mapping study for the Royal Society. (Hereon referenced as Ev. 4, as in Appendix 7.2, published online at www.royalsociety.org/vision)

144 Blakemore, S J 2014 *Adolescent brain development*, 22 January 2014. (See http://thinkneuroscience.wordpress.com, accessed 9 May 2014.)

145 Wellcome Trust 2014 *How neuroscience is affecting education: report of teacher and parent surveys*. London: Wellcome Trust.

146 Ev. 5.

147 *Ibid*. note 145.

Knowing more about brain development might help teachers to decide better 'when to teach what'.

3.5.6 Work experience and careers guidance

Any curriculum structure – no matter how broad – eventually involves choices. Young people can only make informed decisions about the qualifications they should study if they have good quality advice and experience of employment. Helping students develop clear career goals and giving them the skills needed to explore possible future jobs helps them achieve their potential at school or college and make successful transitions after the age of 16.[148]

Young people's aspirations tie in closely with their future occupations.[149] One study found that students were more than three times more likely to gain a STEM degree if they were interested in pursuing science-related careers at age 14.[150] This is particularly important for children from disadvantaged backgrounds, who are less likely to know STEM professionals, and who may not appreciate how the study of science and mathematics can support a range of rewarding careers.

Yet there is a disturbing mismatch between young people's career aspirations with the labour market's current and future needs. Interest in some careers far outweighs the number of vacancies on offer – such as in culture, media or sport. But for manufacturing, even though the sector provides over 10% of all jobs in the UK economy, in one study 0% of 11 – 12 year olds expressed an interest in a career in manufacturing.[151]

Work experience helps students decide on their future career, providing the context and window on roles they may enjoy. As well as developing skills valued by employers, they are also able to seek valuable advice on the qualifications and experiences they might need to achieve their chosen role. STEM work experience also helps academic progression. A study of Russell Group universities found that relevant work experience was essential for entry into undergraduate dentistry and veterinary medicine/science courses, while work experience was desirable for entry into engineering and medicine courses.[152]

148 *Op. cit.*, note 22.

149 *Op. cit.*, note 44.

150 *Ibid*.

151 Mann, A, Massey, D, Glover, P, Kashefpadkel, E T & Dawkins, J 2013 *Nothing in common: the career aspirations of young Britons mapped against projected labour market demand (2010–2020). UKCES and Education and Employers* Taskforce, Occasional Taskforce Research Paper no. 2. (See http://www.educationandemployers.org/media/18037/nothing_in_common_final.pdf, accessed 9 May 2009.)

152 Mann, A, Spring, C, Evans, D &.Dawkins, J 2011 *The importance of experience of the world of work in admissions to Russell Group universities: a desktop review of admissions criteria for six courses*. Education and Employers Taskforce Occasional Taskforce Research Paper no.1, July 2011. (See http://www.educationandemployers.org/media/13853/dave_bevan_conference_paper_2011.pdf, accessed 9 May 2014.)

Relevant and high-quality work experience in STEM sectors should be accessible to every young person, particularly in the state sector.[153] But many work experience placements are actually found by young people or by their families using largely existing social networks.[154] According to a Wellcome Trust survey of 460 young people in 2013,[155] about 40% of 14 – 18 year olds had no work experience, and over 70% had no work experience in STEM.

All young people are entitled to receive good guidance on careers from an early age, and in particular on the opportunities that studying STEM subjects can bring. This is especially important when young people are benefiting from a breadth of education to age 18. Yet only a 'minority' of schools have routinely worked with employers to support teaching and learning, although almost all work with them to support work experience.

The structure and quality of careers guidance varies across the UK. Recent changes in England which make schools responsible for the provision of careers guidance mean that schools need to invest £25,000 per year to deliver the same level of careers guidance previously provided by the UK Government,[156] which used to set aside £450 million for the Connexions careers service.[157] The Gatsby Charitable Foundation has estimated the cost of running effective careers guidance – based on the experiences of other nations who do it successfully – to be £52 per student per year and the savings arising from one fewer young person being unemployed would provide careers guidance to the benchmark level for 280 students.[158]

Under-investment in careers guidance has significant impact on the economy, with the National Careers Council suggesting youth unemployment will cost the exchequer and economic output £28 billion by 2022 in England,[159] with up to £200 million lost per year due to young people choosing the wrong option after compulsory education.[160] More than 60% of 460 young people in the UK aged 14 – 18 questioned in 2012 on behalf of the Wellcome Trust knew little or nothing about careers in science.[161]

153 Students in independent schools typically access higher quality work experience that state school students. See Mann, A 2012 *Work experience: impact and delivery – insights from the evidence*. (See http://www.educationandemployers.org/media/15807/work_experience_report__april_2012_.pdf, accessed 9 May 2014.)

154 *Ibid*.

155 Wellcome Trust 2013 *Wellcome Trust Monitor report. Wave 2. Tracking public views on science, research and science education*. Research report. London: Wellcome Trust.

156 Hilton, F (for Trafford Council) 2012 Written evidence, CG 85. In *Careers guidance for young people, the impact of the new duty on schools*, House of Commons Education Select Committee, seventh report of session 2012–13. London: The Stationery Office.

157 The Connexions service was launched in April 2001 with an annual budget of £450 million. (See http://www.nao.org.uk/report/department-of-education-and-skills-connexions-service-for-all-young-people/, accessed 9 May 2014.)

158 Holman, J 2014 *Good career guidance*. London: Gatsby Charitable Foundation.

159 Hughes, D 2013 The changing UK careers landscape: tidal waves, turbulence and transformation. *Br. J. Guid. Counc*. **41**, 226–239. (See http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3701932/, accessed 9 May 2014.)

160 House of Commons Education Select Committee 2013 *Careers guidance for young people, the impact of the new duty on schools*. Seventh report of session 2012–13, vol. I, p. 9. Report HC 632-I. London: The Stationery Office Ltd.

161 *Op. cit.*, note 152.

3.5.7 Valuing what works

According to the same Wellcome Trust survey, young people view the most useful sources of careers information being family, followed by careers advisers and teachers. Importantly, evidence suggests that knowing 'someone working in the field' is a valued source of careers information,[162] while social connections with employers (Box 10) in the final year of school may also help young people to progress into the workplace.[163]

Having a system of vocational qualifications that gives young people a clear pathway into work, as is exemplified by the German system of vocational education and training, means those studying academic and vocational courses both have excellent and enviable employment chances.[164]

Making a successful transition from education to work is essential if the UK is to reduce rates of youth unemployment. Some countries in Europe seem to manage this better than the UK and this may well be down to their commitment to technical and vocational education.

Some schools in England, including University Technical Colleges (UTCs) and Studio Schools (*viz*. § 3.1), are pioneering new relationships with employers. The first UTC – the JCB Academy in Staffordshire – opened in 2010; the second, the Black Country UTC, opened a year later. There are indications that at least some UTC students achieve better results in core subjects – particularly English and mathematics – than predicted by their previous schools.[165]

Teachers also use practical activities to help younger students start to think about STEM careers and STEM festivals, which engage local employers and the community (*viz*. Box 10).

162 *Ibid*.

163 Jokisaari, M 2007 *From newcomer to insider? Social networks and socialisation into working life. In Youth and social capital* (ed. H. Heleve and J Bynner, J), pp. 175–186. London: Tufnell Press. (See summary at http://www.educationandemployers.org/research/research-reports/all-summaries)

164 Ayres, S, Balaram, B, Parker, I & Eliot, S 2014 *States of transition: youth unemployment, education and labour market policy in Europe and the US* (ed. T Dolphin). London: IPPR.

165 Edge Foundation 2013 *Profound employer engagement in education: what it is and options for scaling it up*. A report for the Board of Trustees of the Edge Foundation by Dr Anthony Mann and Baljinder Virk, Education and Employers Taskforce. (See http://www.edge.co.uk/media/121971/profound_employer_engagement_published_version.pdf, accessed 12 May 2014.)

BOX 10

Embedding careers awareness in all phases of education

Primary Engineer is a programme that encourages primary school children to consider careers in STEM-related professions by bringing industry engineers and engineering challenges into schools and to train teachers to deliver these. Primary Engineer provides classroom resources, including interactive software for smart boards, and schools can take part in annual Primary Engineer regional and national engineering competitions. The programme is designed to help primary and secondary school teachers work together and build links in order to ease the primary-to-secondary transition. It also trains secondary school teachers to help them deliver engineering challenges in their local 'feeder' primary schools.[166]

Careers advice at Bohunt School in Hampshire is designed to give students ambition and help them become 'career ready'.[167] Bohunt, which was adjudged by Ofsted in 2013 to be 'outstanding', runs a weekly STEM club, attended by more than 100 students, as well as a science club for Year 5 pupils from a local primary school. Students at Bohunt go on bushcraft camps and expeditions and the school hosts an annual STEM festival, also open to the local community, involving major STEM employers. The 2014 festival included appearances by TITAN, a 7 ft robot, and a talk on fashion design by the head costume designer of *The Lion King*.

Young people consider the most useful sources of careers information to be family, followed by careers advisers and teachers.

166 See http://www.primaryengineer.com/, accessed 12 May 2014.

167 National Careers Council 2013 *An aspirational nation: creating a culture change in careers provision*. (See http://www.thecdi.net/write/200_National_Careers_Council_report__An_Aspirational_Nation__Creating_a_culture_Change_in_Careers_provison_5th_June_2013.pdf, accessed 12 May 2014.)

A third of the UK science workforce are not graduates, and by 2020 the UK will need approximately 450,000 new STEM technicians.

3.5.8 How work experience and careers guidance should change

A third of the UK science workforce is non-graduate,[168] and by 2020 the UK will need approximately 450,000 new STEM technicians.[169] In order to meet this demand careers advice should promote and raise awareness of the range of vocational options in STEM and their destinations. It is essential that school leaders make careers guidance a priority, and sufficient funding be provided to enable this.

STEM careers awareness should begin at primary school and teachers should make sure there is no bias with respect to gender, race, ethnicity or socio-economic background. Without this, young people can switch off in subjects essential for progress through to a career route they may later aspire to.

If schools are to offer excellent careers advice and work experience they need to have a stronger relationship with employers. This must be a sustained relationship, where both sides influence each other and the link has an influence on how the school is run, the curriculum and its ethos.

Teachers will clearly have different relationships with businesses local to them than to multinational and international employers. Careers advice and work experience must be planned and delivered with the school's local context, as well as the UK's national job market in mind. Local employers will be able to have more direct contact with teachers and students, but larger, national companies provide educational experiences and resources that teachers should take advantage of.

The growth of social media and the importance placed upon them by teenagers offers new and innovative informal ways of delivering careers advice.[170]

3.5.9 The importance of nurturing a positive STEM culture in schools and colleges

Since the culture and ethos of a school or college is steered principally by the leadership team, the responsibility for remediating unconscious bias begins at the top. Surveys have found that more than four out of five schools are perpetuating gender divides between subjects such as biology and physics, while subject uptake is more 'gender neutral' in single-sex schools.[171]

168 Guest, J & Dodd, F 2011 *The current and future UK science workforce. For the Science Council*. Newcastle upon Tyne: TBR. (See http://www.sciencecouncil.org/sites/default/files/UK_Science_Workforce_FinalReport_TBR_2011.pdf, accessed 12 May 2014.)

169 *Op. cit.*, note 22, p. xvii.

170 *Op. cit.*, note 92.

171 Institute of Physics 2013 *Closing doors. Exploring gender and subject choice in schools*. London: IoP.

More needs to be done to engage girls in science and mathematics post-16, but evidence from available UK and international studies is insufficient to support single-sex teaching of science (particularly physics) or mathematics, where prolonged gender imbalances exist.[172] Better gender balance and higher participation in science and mathematics post-16 will more likely be achieved through sustained efforts to embed systemic and cultural change across the educational landscape and counter entrenched cultural prejudices in public life. It also found that unconsciously, gender bias can creep into mixed school culture due to teacher expectations. To counter this, schools must aim to foster a culture of gender balance, particularly in subject choices, and ensure that their teachers expect male or female students to be equally likely to want to pursue biology or physics (Box 11).

BOX 11

Stimulating enjoyment and engagement with physics

The Stimulating Physics Network is run by the Institute of Physics and the Science Learning Centres for students and teachers to improve the quality of physics education and 'reinvigorate' a culture of physics in schools. The network aims to develop young people's appreciation of physics careers, boost their perceptions of physics and increase participation in physics A-level, particularly among girls.

A network of 35 physics coordinators and 35 teaching and learning coaches support road-shows, summer schools and in-school bespoke professional development. An independent evaluation in 2011 found that students from schools involved in the programme were more likely than students from control schools to indicate that they might or would definitely do physics A-level, and that a greater focus on enrichment activities, improved teaching (through increasing the numbers of specialist physics teachers and lab technicians, and more physics-based professional development for non-specialist teachers) together with a reduced emphasis on teaching to the test at GCSE would all help to enhance physics A-level uptake.[173]

Schools must aim to foster a culture of gender balance so that teachers have equal expectations that male and female students will wish to pursue biology or physics.

172 Ev. 3 and Ev. 4. See also Murphy, P & Whitelegg, E 2006 *Girls in the physics classroom. A review of the research on the participation of girls in physics*. London: Institute of Physics.

173 Jenkinson, K, Turner, K, Lambley, C & James, D 2011 *Evaluation of the Stimulating Physics Network*. Milton Keynes and York: Babcock Research. (See http://www.stimulatingphysics.org/pdfs/SPN%20Final%20Report_FINAL.pdf, accessed 12 May 2014.)

Support for science and mathematics must cascade down from school and college leadership teams if these subjects are to flourish.

BOX 12

A demonstration of outstanding subject leadership[174]

Students from Simon Langton Grammar School in Kent make up 1% of the national cohort of physics undergraduates. It is not surprising so many are enthused by the subject – they have the opportunity to take part in astronomy projects thanks to their teacher, Dr Becky Parker, who in 2013 was awarded the Royal Astronomical Society's first Patrick Moore Medal, which recognises notable contributions to astronomy or geophysics by secondary school teachers.

Dr Parker established the school's Langton Star Centre, a suite of laboratories, classrooms and an astronomical observatory, in order to encourage more students to take STEM courses at A-level, to inspire sixth formers to pursue STEM-related courses at university and related careers, to encourage young people to become science teachers, and to give science teachers the chance to conduct research.

Dr Parker, a former head of education at the IoP, raised the £60,000 needed to build the centre's Langton Ultimate Cosmic Ray Detector (LUCID). Pupils have discovered several asteroids near Earth through their Langton Universe Astronomical Research (LUNAR) programme and collaborate with NASA and European Space Agency scientists and schools in the UK and elsewhere in the world.

3.5.10 Leadership for science and mathematics education

Responsibility for excellent science and mathematics teaching rests with school/college governors and head teachers. If science and mathematics are to flourish in schools and colleges, support for these subjects must cascade down from leadership teams.[175]

Subject leadership at any level requires outward-facing individuals who combine excellent subject knowledge, management and administrative skills with the ability to inspire and support their colleagues' work and development (Box 12). This requires that science and mathematics subject leaders undertake formal training – for not enough do so currently[176] – and that this is followed up by a substantial period of mentoring.

The STEM professional community's National Centres infrastructure, which has established itself as a credible, long-standing guardian of these subjects, has a wealth of expertise to share that leadership teams should be drawing on.

174 Ev. 8.

175 Ofsted 2013 *Maintaining curiosity. A survey into science education in schools*. Ref. 130135. London: Ofsted.

176 See http://www.ras.org.uk/news-and-press/219-news-2012/2059-dr-becky-parker-wins-first-ras-patrick-moore-medal, accessed 15 May 2014.

OUR VISION

All young people study mathematics and science up to the age of 18.

Create new baccalaureate-style frameworks that encompass vocational and academic learning across a broad range of subjects to age 18.

RECOMMENDATIONS

- Develop rigorous new post-16 courses and qualifications in mathematics, science, engineering and technology to engage students who are studying non-STEM subjects at school or who are training in the workplace, ensuring these meet the changing needs of employers.
- Increase the amount of time and money invested in practical and problem-solving work in science and mathematics education for 5 – 18 year olds, through access to adequately resourced laboratories and well-trained teachers.
- Extend the age at which students leave formal education or training to 18 in Northern Ireland, Scotland and Wales.

OUR VISION

Students understand the significance of STEM through better careers awareness and guidance.

Maintain investment in large-scale, national programmes and events, delivered locally, which provide students with STEM role models and help teachers and families to develop better engagement with academia and industry.

RECOMMENDATIONS

- Build careers awareness from primary school onwards by giving children exposure to role models, such as professional scientists, engineers and technologists.
- Make careers information, advice and guidance from early secondary onwards an essential part of the school/college week.
- Increase parents' understanding of how STEM offers many and varied employment opportunities for all children, regardless of their social or economic status.

Part four
Quality, coherence and innovation

Significant reforms to the governance of curricula and assessment and changes to accountability systems are required. Teachers should be entrusted with more responsibility for assessing students' achievements.

Left
Practical science at Sittingbourne School .

Quality, coherence and innovation

A National Curriculum should be implemented across all schools and colleges.

4.1 The value of a National Curriculum

National Curricula provide a coherent framework for teaching and learning. They establish the knowledge, skills and understanding that young people are expected to develop over the course of their education, and provide the basis for assessment and awarding of qualifications.

At a meeting at the Wellcome Trust to mark the first 21 years of the National Curriculum (originally introduced in England, Northern Ireland and Wales in 1989), there were some important criticisms (see § 4.2), but a broad agreement that it had had the following significant benefits:

- the first ever national entitlement to science education for all students from ages 5 – 16;
- establishing science as an important core element of the primary curriculum;
- ensuring that students studied all the major scientific disciplines, in particular increasing the number of girls studying physics to the age of 16;
- a raising of standards in many schools;
- improving the continuity and transferability when young people moved from one school to another, whether between phases or geographically.[177]

While schools and colleges should be able to exercise freedom in covering the demands of the curriculum (eg through provisioning of informal learning experiences), it is an important point of principle to expect that a National Curriculum should be implemented nationally across all schools and colleges.

4.2 Stability and innovation in the curriculum for the long term

Stakeholders consulted for this report suggested that politics and education should not mix. Yet state education in the UK consumes over £80 billion a year of taxpayers' money,[178] and it is right that policy should be determined by politicians whom taxpayers have elected.

History shows that educational reform results from differences in political ideologies, when a national government changes or when a new Secretary of State for education is appointed. Since the UK Government introduced the National Curriculum to schools in England, Northern Ireland and Wales in 1989,[179] there have been at least ten reforms to the curriculum and national assessment in England alone.[180] In Wales, Northern Ireland and Scotland, wholesale changes to the national curricula have taken place during the past six years and a new National Curriculum is being introduced in England from this September.

177 Wellcome Trust 2010 *Leading debate: 21 years of the National Curriculum for science*. London: Wellcome Trust. (See http://www.wellcome.ac.uk/About-us/Publications/Reports/Education/index.htm, accessed 25 April 2014.)

178 Department for Education 2013 *Education and training statistics for the United Kingdom 2013*, p. 21. Ref. V01/2013. (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255083/v01-2013.pdf, accessed 12 May 2014.)

179 In 1989, England, Northern Ireland and Wales had the same education system. This changed following the transfer of education powers from the UK parliament to the Northern Irish and Welsh Assemblies in 1999.

180 See www.legislation.gov.uk, accessed 12 May 2014.

Science and mathematics curricula must of course be revised, if only to keep up with changes in subject content, but too frequent changes in curriculum and assessment absorb the time and energy of teachers that could usefully be spent preparing more inspiring lessons or on professional development to improve teaching and encourage innovation.

These changes have resulted in teachers feeling disempowered and disillusioned, giving them a strong sense of over-prescription and increased pressure to 'teach to the test', ultimately compromising young people's educational experience.[181]

Accordingly, the focus here is on improving mechanisms for developing policy concerning curricula and assessment and associated changes to accountability frameworks. The aim is to ensure a dynamic and high-quality curriculum that evolves over time but does not require frequent radical change. This stability is essential to protecting and nurturing excellent teaching and learning.

It is vital that national curricula should be continually monitored and reviewed, in order to ensure:

- their content keeps pace with new knowledge and understanding;
- there is coherence between closely linked disciplines, such as within the sciences and between science and mathematics; and
- that assessment is appropriate to the content of the curricula and is geared to supporting learning and measuring accurately the knowledge, skills and understanding young people are expected to develop.

This should help reduce the need for large-scale review and reform. However, any major or wholesale changes to curricula should be managed in a more measured way over longer time-scales than political cycles.

Politicians, employers and the public need to appreciate that the true impact of major curriculum reform may only become clear after a number of years, particularly given the need for teachers to adapt to the new requirements and the time taken for at least the first full cohort of students affected by the reforms to complete their passage through school.

Equally, the introduction of new curricular innovations should be based on:

- analysis of comprehensive performance statistics;
- the findings of a coordinated programme of planned short-term studies and longitudinal research evidence;
- full and proper consultation with the education community and the wider public; and
- robust piloting of new interventions and careful consideration of independently conducted evaluations.

Any major changes to curricula should be managed over longer time-scales than political cycles.

181 *Op. cit*, note 177.

The stability of newly established curricula may only be guaranteed over lengthier time-scales than the five year parliamentary cycles that now operate across the UK's jurisdictions. In fact, research into unsuccessful curriculum reforms internationally has pointed to a failure to recognise the long time-scale involved in achieving systemic educational reform.[182] Indeed, the science and mathematics education communities believe that the quality of the new National Curriculum in England has suffered due to a lack of clarity and transparency in the review process.[183]

National curricula in science and mathematics should be the collective responsibility of the STEM community, politicians of all mainstream parties and other relevant agencies. All of these stakeholders should work closely together to ensure that the decisions they take are informed by robust evidence and practice. This is increasingly important given the substantial reduction in the size of – and likely loss of educational expertise from – the civil service.[184]

At present, the scope for the STEM community to influence national curriculum development, implementation and monitoring varies according to the different ways in which national curricula are managed across the UK (Box 13). The STEM education community can offer both resource and expertise to inform curriculum development and its assessment across the UK, and the next section develops the concept for new infrastructures to support better management of the national curricula in England and Wales.

4.3 The role of the STEM community

It is proposed that the expertise of the STEM professional bodies should, under a strong overarching body, be used to stabilise the curriculum and assessment, providing a platform for excellent science and mathematics teaching.

STEM professional bodies are well placed to define and defend the content and standard of their subjects. These include the Institute of Physics (IoP), the Royal Society of Chemistry (RSC) and the Society of Biology, the professional engineering institutions together with, in mathematics, the independent Advisory Committee on Mathematics Education (ACME) and the professional bodies and learned societies represented on the Council for Mathematical Sciences (CMS).[185]

Each of these bodies counts academics, teachers and employers among its members and has a long history of expertise in its subject. In addition, the Institute of Mathematics and its Applications (IMA), the IoP, Society of Biology and RSC already validate university degree courses in their subjects, so they know about regulating the content and standards of qualifications and have gained the trust of universities and employers. The same applies to the engineering institutions.

182 TISME 2014 Involving stakeholders in curriculum reform. Five ideas for change debate and planning for the future of STEM education. Conference paper, 28 January 2014.

183 SCORE 2013 Letter to Elizabeth Truss MP, Parliamentary Under Secretary of State for Education and Childcare on the National Curriculum review process, 8 August 2013 (See http://www.score-education.org/home, accessed 21 February 2014).

184 Thomas, P, Kidson, M & Wright, W 2013 *Civil service reform. One year on*. London: Institute for Government.

185 The Council for the Mathematical Sciences (CMS) comprises the Edinburgh Mathematical Society (EMS), the Institute of Mathematics and its Applications (IMA), the London Mathematical Society (LMS), the Operational Research Society (ORS) and the Royal Statistical Society (RSS).

BOX 13

National infrastructures for managing National Curricula in the UK

England and Wales

There have been independent advisory bodies in England and Wales, namely the Qualifications and Curriculum Development Agency (QCDA), which was preceded by the Schools Council, the National Curriculum Council, the School Examinations and Assessment Council (SEAC), the School Curriculum and Assessment Authority and the Qualifications and Curriculum Authority (QCA) and the Qualifications, Curriculum and Assessment Authority (ACCAC) for Wales. But their work was inadequately informed by subject specialist advisory groups with, for instance, the science and mathematics specialist teams in QCA being disbanded in 2006. In 2011 and 2006, respectively, their functions were absorbed into the Department for Education and the Welsh Government's Department for Children, Education, Lifelong Learning and Skills (DCELLS), now the Department for Education and Skills (DfES).

Since then, there has been no independent body advising on the curriculum and assessment in England or Wales. Instead, both the UK Government and Welsh Assembly Government have sought occasional advice from specific professional bodies or groups of subject experts, eg in respect of establishing new computing curricula.

Scotland

In Scotland, Education Scotland is the executive agency established by the Scottish Government to advise it on the curriculum, its assessment and other matters. In addition, the Scottish Government established the STEM Education Council (STEMEC) as an independent adviser, 'to help build partnerships and alliances between the diverse organisations and professions supporting and delivering education…', and with a current remit covering interdisciplinary learning, initial teacher education, professional learning communities, primary science and continuing professional development. Crucially, its membership is widely drawn, from the academic STEM community, industry, schools and Education Scotland.

Northern Ireland

In Northern Ireland, the Council for the Curriculum Examinations and Assessment (CCEA) is charged with convening representatives from the STEM community to advise the Department of Education Northern Ireland (DENI) on the curriculum and assessment, although the Department may also choose to seek advice separately from, for instance, employers or the Education and Training Inspectorate (ETI).

In England, the Department for Education (DfE) started down the road towards independence for A-levels in 2012, when the Secretary of State stated his wish for control of A-levels to be passed to universities. This intention was welcomed, though it has proved hard to implement in practice. Control of A-levels has now fragmented across the Russell Group of universities, the DfE, the examinations regulator, Ofqual, and the examination boards.

An opportunity has been missed by failing to give the professional bodies the key role in the development of A-level sciences and mathematics. This opportunity should be revisited. The proposals that follow begin with the sciences and mathematics, which are the particular concern of the Royal Society, and which comprise two out of the three core subjects in the National Curriculum in England. However, these proposals could be extended to include other subjects – such as those in the arts, humanities and the social sciences – and the Royal Society remains open to discussion with other subject communities in this regard.

4.4 Subject committees for the sciences and mathematics

In the light of the important differences in the education systems between the four nations of the UK, the initial proposition concerns post-16 education in England and Wales. The professional bodies would convene subject committees to address the curriculum for A-levels across the sciences and mathematics, including the new A-level in Engineering currently in development with the Royal Academy of Engineering (RAEng). In time, the principle could be applied to the curriculum and assessment for science subjects and mathematics at all levels and include vocational qualifications.

At the subject level, the long-term development of the content and assessment of A-levels in the three core sciences (biology, chemistry and physics) should be entrusted, respectively, to the Society of Biology, RSC and IoP. In the case of computer science, the British Computer Society (BCS) and UKForCE[186] are key. There is no single professional body for mathematics, but the CMS and ACME are good starting points.

The professional bodies would each convene a standing subject committee for the major sciences (physics, chemistry, biology and computer science) and mathematics, with representation from universities, employers, schools and colleges. Indeed work has already begun with the subject committees established in 2013 by the IoP, RSC and Society of Biology.

186 The UK Forum for Computing Education (UKForCE) will provide an independent and unified voice to advise UK government and other agencies on issues relating to computing education. It was established in 2013, in response to a recommendation in the 2012 Royal Society– Royal Academy of Engineering report, *Shutdown or restart? The way forward for computing in UK schools*.

Examination boards would be required to consult with the subject committees during the development of their specifications, and to submit the draft specification for their approval before final submission to Ofqual.

Having established the subject criteria and approved specifications, the subject committees would continue in existence indefinitely, to review the application of the criteria and ensure that they remain up to date. They would monitor the content and standards of live A-level examinations in their subject, and alert examination boards and Ofqual to any concerns about the quality and standard of examinations in any particular specification.

Each subject committee would draw on research evidence, and commission new research, if needed, to enable it to take a long-term view. At any time, it would have a considered position on the current state of the evolution of the qualification(s) it is reviewing, and the next phase of their development. This would end the current stop–start evolution of the curriculum and qualifications. There would be an agreement that the curriculum and assessment would change no more frequently than, say, once every five years.[187]

There have been positive reports of the work that has already been started by the A Level Content Advisory Board (ALCAB).[188] This work could be seen as an excellent starting point from which to bring these proposals to life.

4.5 New independent curriculum and assessment bodies for England and Wales

At a general level, there should be overarching curriculum and assessment bodies responsible for setting out broad criteria to ensure fundamental equity and consistency of standards between subjects, and coherence across the curriculum. These bodies would work alongside, but would not replace, the qualifications regulators Ofqual (in England) and (come the end of 2015) Qualifications Wales. While the independent bodies would scrutinise the examinations, the regulators would retain exclusive regulatory control of and be responsible for ensuring consistent standards between examination boards.

Although history relates (Box 13) that independent bodies for managing curriculum and qualifications policy in England and Wales were short-lived, an independent overarching body, duly informed by professional subject expertise as described in § 4.4, is required to achieve coherence and consistency within and across subjects.

An independent over-arching body, informed by professional subject expertise is required to achieve coherence and consistency within and across subjects.

187 There is a precedent for this in the curriculum review carried out by Ron (later Lord) Dearing in 1994, with an agreement that there should be no more change for five years after the review – although this only happened once. (The Dearing Review can be found at http://www.educationengland.org.uk/documents/dearing1994/dearing1994.html, *viz*. paragraphs 2.13 and 4.54, accessed 12 May 2014.)

188 ALCAB was set up by the Russell Group of universities to provide advice to Ofqual 'on the core content requirements considered desirable in A level facilitating subjects for adequate preparation for leading universities'. (See http://alcab.org.uk/, accessed 12 May 2014.)

> “Remember, school is an experience not an exam.”
>
> Beth, young person[189]

To work effectively, the overarching body would need to:

- provide advice on the curriculum, its assessment, and the accountability framework within which these operate, (note: all three interact together and it is not possible to consider the curriculum in isolation from the other two);
- achieve cross-party agreement for the new arrangements, in particular concerning the requirement that the curriculum and its assessment would change no more frequently than once every five years;
- be demonstrably independent, with a strong chair of great personal standing;
- comprise a small high-quality committee made up of senior people representing employers, academics and teachers with strong credibility among political parties;
- agree all appointments to this committee by Opposition parties as well as Government, confirmed by, respectively, the House of Commons Education Select Committee and the Welsh Government’s Children, Young People and Education Committee;
- confirm long-term appointments, perhaps for seven years, or in an era of five year fixed-term parliaments, five year appointments made mid-parliament, eg May 2017 (for England) and May 2018 (for Wales); and
- draw on authoritative evidence in making its recommendations, as do the National Institute for Health and Clinical Excellence (NICE) and the Monetary Policy Committee (MPC) in their respective spheres.

4.6 Trusting teachers to assess achievement in science and mathematics

Making the radical changes to curriculum frameworks discussed in part three and the governance of National Curricula set out in §§ 4.2 – 4.5 need to be paralleled by changes to how curricula are assessed. This is because current approaches to assessment are not satisfactory. For while testing plays an important role in learning and development, its often high-stakes nature,[190] coupled with the additional pressure schools are under to achieve the highest possible rankings in published league tables, results in teachers ‘drilling’ their students in the essential subject content required for a pass (for instance, in end of Key Stage tests undertaken in primary education).[191, 192] This exclusive focus on ‘teaching to the test’ results in a narrow curriculum that impoverishes young people’s breadth and balance of learning.[193, 194]

Of course, high-stakes testing is necessary to evidence young people’s knowledge, understanding and skills, but this should not undermine the purpose of the curriculum.[195]

189 Pearson and Teach First 2013 *My education*. (See http://uk.pearson.com/content/dam/ped/pei/uk/pearson-uk/Campaigns/myeducation/my-education-full-report.pdf, accessed 12 May 2014.)

190 ‘High stakes’ refers to public examinations in which students’ performance is likely to have implications for their progression and employment prospects.

191 *Op. cit.*, note 32.

192 Alexander, R (ed) 2010 *Children, their world, their education. Final report and recommendations of the Cambridge Primary Review*. London: Routledge.

193 *Ibid*.

194 Oates, T 2010 *Could do better: using international comparisons to refine the National Curriculum in England*. Cambridge: Cambridge Assessment.

195 *Ibid*.

The effect of National Curriculum reform (certainly in England) has seen assessment of learning prioritised over assessment for learning. A better balance between the two is required, with multiple measures of student and school/college performance to relieve the pressure of high-stakes assessment and to help ensure reliable and valid data (*viz*. § 4.7).[196]

Many of the world's successful education systems (eg Finland, New Zealand, Singapore and Ireland (Box 14)) entrust teachers with great responsibility for assessment, with school-based performance assessments often helping to improve teaching.[197]

BOX 14

Curriculum and assessment policy in Ireland

Ireland has one of Europe's most successful education systems, coming 4th in reading, 9th in science and 13th in mathematics out of 34 OECD countries in the 2012 PISA exercise.

The school curriculum and assessment are determined by an independent body, the National Council for Curriculum and Assessment (NCCA). The Board of the NCCA has wide representation across schools, universities and employers, and the organisation has a specialist staff of 26 who are often seconded teachers. NCCA makes recommendations for change in the curriculum and assessment to the Minister for Education and Skills, who normally accepts their advice. NCCA's recommendations are based on extensive research and enjoy cross-party support, though they are sometimes contested by the teaching unions.

Under current arrangements in secondary schools, there are two externally tested certificates: Junior Certificate taken at age 14, and Leaving Certificate taken at age 18.

Following wide consultation and much research by NCCA, Education Minister Ruairí Quinn has now decided to make the Junior Certificate a fully teacher-assessed qualification, with effect from 2015, while retaining external assessment for the Leaving Certificate. The rationale for this decision is that the staying-on rate is now so high (over 90%) that Junior Certificate is effectively a staging post on the route to the critically important Leaving Certificate. Under the new arrangements, the Leaving Certificate in science, for example, will be determined by a written examination (70% weighting) and a practical examination administered by teachers from other schools who have been trained for the purpose. The practical examination will be trialled during the coming school year, prior to full-scale implementation.

The new arrangements towards which Ireland is travelling have parallels with the proposals described in this report for the UK: a system that makes greater use of teacher assessment at age 16 while retaining a strong element of external examination at age 18.

198 NFER & Arad Research 2013 *A rapid evidence assessment on the impact of curriculum and assessment arrangements within high performing countries*. Llandudno Junction: Welsh Government.

199 *Ibid*.

> “**Examinations are only a snapshot of academic performance. A World Cup with only one match. A tennis match with one service. To achieve one’s potential, everything has to be perfect on the day.**”
>
> Abdul Jawula, 18-year-old student[198]

The Expert Panel established to advise the UK Government during its recent review of the National Curriculum in England showed there is an accumulating wealth of evidence from within the UK’s education systems and other international educational jurisdictions indicating that teacher assessment can be more reliable and more valid than external examinations.[199]

Formative or ongoing assessment by teachers using everyday tasks set in the classroom is a hallmark of outstanding teaching and learning. While it should be an integral part of the teaching every child receives throughout their schooling, teachers’ skills in assessing students’ development and progress should also be deployed in high-stakes assessment.

The UK’s education systems should gradually move to a point at which teachers are given predominant responsibility for assessing students’ progress and level of achievements.

But, more than this, teachers should also be involved in assessing and moderating the outputs of students in other classes and schools, as happens in, for instance, New Zealand (Box 15) with the work anonymised to avoid bias. This would have the further benefit of enabling teachers to collect better evidence individually and collectively about what works best in education. The use of teacher judgements is best when enhanced by statistical cross-validation. This already happens in many nations.

For example, in Hong Kong, statistical models are used to adjust school-based assessment scores of students when they are compared to the students’ public examination scores. Samples of their work are also inspected by professional moderators.

Completing this transition in respect of the Vision set out in this report would necessitate:

- extending compulsory education and training to age 18 across Northern Ireland, Scotland and Wales, following England’s lead in legislating for this;
- adoption of new curriculum frameworks (part three);
- emphasising training in assessment within initial teacher education courses and professional development;[200]
- adoption of effective practices of teacher evaluation, with a view to fostering a culture of self-reflection and improvement (eg through professional development) within the teaching workforce; and
- introducing a leaving certificate as the main record of school and/or college achievement, including demonstration of competence in English, mathematics and science.

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198 *Op. cit.*, note 185.

199 James, M, Oates, T, Pollard, A & Wiliam, D 2011 *The Framework for the National Curriculum. A report by the Expert Panel for the National Curriculum review*. London: DfE.

200 Schleicher, A 2013 Effective teacher evaluation: transforming a game into a game-changer. In *Teachers for the 21st century: using evaluation to improve teaching*. Paris: OECD.

BOX 15

Ensuring high-quality teacher assessment in New Zealand

In New Zealand, student assessment is teacher-led until upper secondary school, when more formal methods are used to provide information to employers and other educational institutions. Methods of teacher assessment are developed internally by schools, and are based on the professional judgement of teachers using information gathered from day-to-day teaching and the use of nationally validated assessment tools.

Teachers are supported to do this. They can use Assessment Resource Banks (ARBs), collections of classroom assessment resources in English, mathematics and science developed by the New Zealand Council for Educational Research. The Ministry of Education sets evaluation and assessment guidelines.

Teachers assess students twice a year to see if they are meeting national expectations. The first is called a ‘progress towards’ report and the second is a final assessment. Teachers can use formal and informal information to judge progress, and they report this to parents. The New Zealand Qualifications Authority employs more than 34 full-time equivalent moderators and 235 part-time moderators to check teacher assessment. Most moderators are current or recent teachers and all are assessment experts in particular subjects. Schools can ask for clarification or appeal a moderator’s decision. In 2009 and 2010, fewer than one in 1,000 moderator judgements were successfully appealed.

4.7 Assessing science and mathematics

In addition to the generic concerns about assessment discussed in § 4.6, there are more specific issues about how science and mathematics are assessed, with current arrangements (and those currently being developed for A-level in England) being unsuitable because they do not reflect the practical and problem-solving nature of these subjects.[201, 202]

As the Council for Science and Technology (CST), which directly advises the Prime Minister, stated: ‘practical laboratory work is the essence of science and should be at the heart of science learning… pressures to perform in public examinations – especially at GCSE and A-level – are pushing inspiring practical work into the margins as teachers concentrate on preparing for examinations’.[203]

201 Winston, R 2014 Interview on Radio 4’s Today programme (10 April 2014).

202 Gatsby Foundation and Wellcome Trust 2013 *Policy note: assessment of practical work in science*. (See http://www.gatsby.org.uk/~/media/Files/Education/Practical%20Science%20Policy%20Note.ashx, accessed 1 May 2014.)

203 Council for Science and Technology 2013 Letter to Michael Gove on how best to education future scientists and engineers, 31 July 2013. (See https://www.gov.uk/government/organisations/council-for-science-and-technology, accessed 13 November 2013.)

> “To get a good grade you do not have to be a good scientist – just a good memory.”
>
> Young person[204]

Science and mathematics education should allow young people to engage with these subjects for themselves through experimentation and observation.

Assessment in science and mathematics should seek to measure how scientifically and mathematically informed students are (*viz*. part two of this report). The CST has advocated that a mixed-methods approach should be taken to teaching and assessing practical science, in keeping with educational practices in high-performing overseas jurisdictions (eg Finland, China, New Zealand and Singapore).[205]

In these nations teachers use continuous, classroom-based work; project work; and ICT-based methods to assess children's progress, in addition to conducting externally imposed standardised tests to monitor school performance.[206] There is a suggestion that young people would support this approach, with a survey of 8,000 teenagers in the UK concluding that end-of-year examinations are not the best way to assess learning.[207]

Practical science assessment should be through a mixed-methods approach involving written, investigative and oral tests (Appendix 7.9), and would increasingly be expected to involve the sort of innovative computer-based approaches found across the world.

Similarly, summative assessment of mathematics should involve testing a variety of knowledge, understanding and skills, including 'testing students' abilities to design, plan, estimate, evaluate and recommend, review and critique, investigate, re-present information, explain, define concepts and show their skills in routine technical exercises'.[208] A set of eight principles for assessing students' mathematical abilities has been identified (Appendix 7.9).

4.8 The relationship between assessment and accountability

Using high-stakes assessment to measure the overall performance of an education system can lead to impoverished learning because teachers, who are invariably under considerable pressure to meet targets, will teach formulaically[209] and to the test,[210] unless they are 'exceptional' and 'have the support of management in their schools to work in ways that [are] not always focused on short-term test results'.[211]

204 *Op. cit.*, note 35.

205 CST 2013 Letter to Michael Gove on how best to education future scientists and engineers, 31 July 2013. (See https://www.gov.uk/government/organisations/council-for-science-and-technology, accessed 13 November 2013.)

206 *Op. cit.*, note 196.

207 *Op. cit.*, note 189.

208 Shell Center for Mathematical Education, University of California at Berkeley and the University of Nottingham (see http://map.mathshell.org.uk/materials/index.php, accessed 1 May 2014.)

209 *Op. cit.*, note 1.

210 Reynolds, D & Kelly, A 2013 Accountability and the meaning of 'success' in education systems and STEM subjects. A report for the Royal Society. (Hereon referenced as Ev. 1, as in Appendix 7.2, published online at www.royalsociety.org/vision.)

211 ACME 2011 *Mathematical needs. The mathematical needs of learners*, p. 22. London: ACME.

Teaching to the test in primary and secondary education is associated with reducing interest in and narrowing the curriculum.[212, 213]

Test results improve because students become familiar with the demands of exams, rather than because they have genuinely improved their learning.[214] Research has also shown that testing has led to students spending less time on scientific enquiry[215, 216] and to a reduced focus on using and applying mathematics.[217] This has led to children not being equipped 'well enough mathematically for their futures'.[218]

It has also created problems with primary–secondary school transition. Secondary school teachers lack trust in the attainment data provided by primary school teachers, and sometimes carry out their own tests of all children.[219]

As Sir David Bell, former Chief Inspector of Schools and Permanent Secretary at the Department for Education in England, has said: "It is important not to overemphasise accountability as a means of driving up performance… Too often in the past, there has been a tendency to see inspection and other forms of accountability as a 'cure-all' which can demoralise teachers who see added burdens without the requisite support."[220]

Summative assessment must give young people a more useful snapshot of their skills, and encourage enthusiasm and practical engagement with science and mathematics rather than just the memorising of facts. The Royal Society's vision is for summative assessment to be led by teachers, moderated in the ways which have been successful in other nations.

"The challenge is always to hold schools accountable on the core aspects of teacher professionalism, while not stifling local innovation and teacher creativity."

Professor Andreas Schleicher, Deputy Director for Education and Skills, OECD[221]

212 Alexander, R 2010 *Children, their world, their education. Final report and recommendations of the Cambridge Primary Review*. Abingdon, Oxon: Routledge.

213 House of Commons Children, Schools and Families Committee 2008 *Testing and assessment, vol. I. Report, together with formal minutes*. Third report of session 2007–08. Ref. HC 169-I. London: The Stationery Office Ltd.

214 Green, S & Oates, T 2007 *How to promote educational quality through national assessment systems*. A paper presented at the International Association for Educational Assessment Annual Conference, Baku, Azerbaijan, September 2007.

215 Science Community Representing Education 2008 *Practical work in science: a report and proposal for a strategic framework. Executive summary*. London: SCORE.

216 House of Commons Science and Technology Committee 2011 *Practical experiments in school science lessons and science field trips, vol. 1*. Ninth report of session 2010–12. London: The Stationery Office.

217 Advisory Committee on Mathematics Education 2013 *GCSE mathematics: an overview of the Advisory Committee on Mathematics Education's advice*. (See http://www.acme-uk.org/media/11434/acmegcsemathematicsjun13.pdf, accessed 13 May 2014.)

218 Ofsted 2008 *Mathematics: understanding the score*. London: Ofsted.

219 Evangelou, M, Taggart, B, Sylva, K, Melhuish, E, Sammons, P & Siraj-Blatchford, I 2008 *What makes a successful transition from primary to secondary school? Effective pre-school, primary and secondary education 3–14 project (EPPSE 3–14)*. Research report DCSF-RR019. London: DCSF.

220 Bell, D 2014 Summary of the discussions, p. 9. In *Visions for improving accountability in education. Summary report and related papers from a joint Royal Society–Wellcome Trust expert seminar held at the Wellcome Trust on 16 May 2013*. London: Royal Society. (Published online at www.royalsociety.org/vision)

221 Schleicher, A 2013 Summary of the discussions. In *Visions for improving accountability in education. Summary report and related papers from a joint Royal Society–Wellcome Trust expert seminar held at the Wellcome Trust on 16 May 2013*. London: Royal Society. (Published online at www.royalsociety.org/vision)

Schools and colleges should be judged by a wider range of measures.

The way schools and colleges are held accountable should build trust among governments, schools and colleges, teachers, parents and students by providing a rich and transparent picture of the education system; promote student progression and effective education; and support schools and colleges to be innovative and provide excellent and inspiring teaching.

Research for this report has shown that, in addition to sensible and proportionate use of measures of assessment, there is a need to increase the range of science- and mathematics-relevant measures upon which schools and colleges are judged.[222] Indeed, the Wellcome Trust has concluded that: 'At best, current systems of accountability based on benchmarking a narrow range of indicators have little impact on improving science education.'[223] A wider range of accountability measures should drive students' progress and an institution's all-round excellence in education. Some suggestions as to what these might involve are included in Table 4.

However, improvement depends on having enough high-quality teachers.[224] Reforms to initial teacher education and professional development proposed here should equip teachers with the subject knowledge and pedagogical skills to work within this new system of accountability, which hopefully will pervade the UK's schools and colleges by 2030.

Its hallmarks would include a reduced focus from governments and inspectorates on high-stakes accountability measures based on testing, and in its place, more coherent methods to assess the performance of students, teachers, head teachers and college principals, the overall performance of schools and colleges and of education systems. Parents, students and employers would be more involved in evaluating the quality and performance of schools and colleges.

222 Ev. 1.

223 Wellcome Trust 2013 *Perspectives on Education: effects from accountabilities*. London: Wellcome Trust.

224 Bell, D 2014 School accountability: today and tomorrow. In *Visions for improving accountability in education. Summary report and related papers from a joint Royal Society–Wellcome Trust expert seminar held at the Wellcome Trust on 16 May 2013*. London: Royal Society. (Published online at www.royalsociety.org/vision)

TABLE 4

A broader accountability framework for science and mathematics education

Inspectorates

Inspectors should concentrate on assessing through representative sampling the overall quality of the teaching and learning of science and mathematics in schools and colleges. They should undertake explicit action to counteract any unconscious bias they may encounter concerning expectations of achievement based on gender, race or socio-economic background.

Metrics that could be checked by inspectorates and/or included in performance tables

In these subjects, their focus should be strongly on:

- practical work and problem-solving (including the quality of laboratories and adequacy of equipment);
- the use of digital technologies in innovative teaching practice;
- the enthusiasm students show for these subjects;
- the range of access to and quality of careers-oriented experiences, information, advice and guidance;
- the extent to which these institutions engage with local community employers, including industry, and the quality of this engagement;
- students' progression in these subjects (including destinations), including by gender;
- the numbers of students pursuing the various combinations of science and mathematics options on offer;
- levels and quality of staffing;
- the extensiveness of cross-departmental working and support;
- the amount of subject-specific professional development being undertaken by teachers; and
- efforts to widen participation in mathematics and science for under-represented groups, eg girls in physics.

Inspectorates should help empower head teachers and principals to support innovative teaching practices, teachers' participation in educational research, and a 'can do' ethos among teachers and students. Inspectorates should also make available the evidence upon which their judgements are based.

School or college governing body

Membership should include at least one scientist, mathematician, or someone who uses science or mathematics in their job.

School/college leadership and ethos

Governors have a dual role: to support the leadership team, and to hold it to account for the institution's performance. Since it is the governing body that appoints head teachers or principals – who in turn appoint the staff – governors have a huge responsibility for:

- the ethos that develops within a school or college, the attitude and excellence of the teaching staff, the quality of subject-specific teaching and learning and students' progress;
- the extent to which a positive culture towards professional development exists and is promoted by subject leaders;
- the extent to which expertise in science and mathematics teaching is shared with other schools and colleges;
- the strength of links with local employers; and
- the extent to which parents are encouraged to support their children's science and mathematics education (particularly at primary level).

OUR VISION

Curricula and their assessment are stabilised and support excellent teaching and learning.

Use the expertise and independence of the STEM professional bodies, under strong overarching bodies, to stabilise the curriculum and assessment, providing quality and coherence in 5 – 18 science and mathematics education.

RECOMMENDATIONS

- Establish new, independent, expert bodies in England and Wales, and enhance existing structures in Northern Ireland and Scotland, to provide stability in curriculum and assessment and allow teachers space to innovate in their teaching.
- Commit to invest in these bodies long term years to enable STEM experts, including employers, to contribute their knowledge and experience.

OUR VISION

The success of students, teachers and education systems is judged through appropriate and broadly based assessment and accountability measures.

Ensure teachers have an increased role in assessing student achievement in public qualifications. Judge the health of the school and college systems through broader measures including ones that reflect the features of high quality STEM education.

RECOMMENDATIONS

- Entrust teachers with increased responsibility for assessing students' achievements.
- Place practical work and problem-solving at the heart of good assessment of science and mathematics.
- Use a wider set of measures than examination performance to make more informed judgements about the quality of a school or college.
- Measure the quality of science and mathematics provision in schools and colleges through specific STEM-related indicators, such as tracking the number and diversity of students taking STEM qualifications to 16 and post-16.
- Require all school and college governing bodies to have at least one member with STEM subject expertise.
- Increase the emphasis in school and college inspections on identifying and sharing good practice.


20M/S
A
B
STAFF

Part five
Inspirational science and mathematics teaching

Teachers have a crucial role to play in realising our Vision. Ensuring the UK has an adequate supply of science and mathematics teachers is dependent on supporting professionalism in teaching and raising its status.

Left
A science lesson at Copland Community School.

Inspirational science and mathematics teaching

5.1 Recognising the professionalism of teachers

Teachers have the privilege and responsibility of developing young people and preparing them for their future lives. Teaching is a highly skilled and multifaceted occupation combining motivational, organisational, administrative, communication and management skills. It requires a high intellect, dedication, and enormous depths of concentration, energy and patience and the ability to move seamlessly between the roles of coach, counsellor, minder and disciplinarian on a daily basis.

Yet in the UK, teachers are generally held in less esteem than their peers in many other countries,[225] and teaching is often considered a less enticing option than other, higher-salaried professions.[226] This situation is exacerbated whenever there is an upturn in the global economy, and is particularly the case for STEM graduates, who are continuously in short supply in the UK and highly sought-after by employers.

Unlike other professions, teaching has historically lacked a clear career structure and qualifications framework. Opinion is divided on the importance of professional qualifications for teachers and many feel that teachers should simply train on the job. In England, academies and free schools, which now account for more than half of all state-sector secondary schools, are not required to employ qualified teachers.

A dramatic change in political and public attitudes towards the profession over the next 20 years is needed to ensure that teaching becomes a high-status profession and can attract a healthy supply of excellent science and mathematics specialist teachers.

5.2 The supply of science and mathematics teachers

As was acknowledged in part three, the UK's capacity to offer a high-quality science and mathematics education to all young people is hampered by shortages of suitably qualified teachers that have persisted for many years.[227, 228, 229]

225 Varkey GEMS Foundation 2013 *2013 global teacher status index*. London: Varkey GEMS Foundation.

226 Royal Society 2007 *The UK's science and mathematics teaching workforce. A 'state of the nation' report*. London: Royal Society.

227 Ev. 7.

228 *Op. cit.*, note 226.

229 Royal Society 2010 *Science and mathematics education 5–14. A 'state of the nation' report*. London: Royal Society.

5.2.1 Primary science and mathematics teachers

The quality of UK primary science and mathematics education is affected by the lack of teachers with relevant expertise in these subjects. According to a recent count, just 3% and 5%, respectively, of England's primary school teachers hold specialist mathematics or science degrees and teaching qualifications in these subjects. In Wales only 10% of all primary teachers registered with the General Teaching Council for Wales (GTCW)[230] reportedly have a degree in mathematics or the sciences.[231] In Scotland, the censuses merely indicate the numbers of primary teachers in publicly funded schools who have stated that they primarily teach biology, chemistry, physics, science or mathematics. The indication is that 'only a tiny fraction of the primary teaching workforce in Scotland may be represented by teachers holding degrees in science and mathematics'.[232]

5.2.2 Secondary science and mathematics teachers

England and Wales suffer from inadequate numbers of suitably qualified mathematics, computer science, chemistry and physics teachers.[233, 234, 235] The figures from England's latest School Workforce Census, conducted in November 2013, showed that more than 20% of mathematics and chemistry teachers, a third of physics teachers and more than half of ICT teachers in state-funded schools in England have no relevant post-A-level qualification in the subject.[236] In Scotland and Northern Ireland, demand and supply are reported to be balanced.[237]

The quality of UK primary science is affected by the lack of teachers with relevant expertise.

5.3 The importance of subject specialism

Inspirational teaching begins with 'teachers who know and love their subject'.[238] All those who teach science and mathematics – whether at primary or secondary level – should have an understanding of scientific and mathematical concepts to meet the demands of the curriculum. They should be confident in using scientific and mathematical terminology, undertaking practical or mathematical reasoning and modelling work, researching topics in their subjects and helping their students to do likewise.

230 Following the Education (Wales) Act 2014 being granted Royal Assent, the GTCW is being reconfigured as the Education Workforce Council (see http://wales.gov.uk/newsroom/educationandskills/2014/8766080/?lang=en, accessed 14 May 2014.).

231 Elizabeth Brimble, Qualifications and Registration Manager, GTCW, personal communication, 9 October 2013.

232 *Op. cit.*, note 229.

233 *Op. cit.*, note 81.

234 Royal Society 2010 *Primary science and mathematics education: getting the basics right. A summary of the key issues in 5–11 education from the Royal Society's 'state of the nation' report on 5–14 science and mathematics education in the United Kingdom*. London: Royal Society.

235 Murphy, C & Beggs, J 2005 *Primary science in the UK: a scoping study. Final report to the Wellcome Trust*. London: Wellcome Trust.

236 Department for Education 2014 *School workforce in England 2013. Statistics on the size and characteristics of the schools' workforce in state-funded schools* (SFR11/2014). London: DfE.

237 Ev. 7.

238 Department of Business, Innovation and Skills 2010 *Science and mathematics secondary education for the 21st century. Report of the Science and Learning Expert Group*. London: DBIS.

Science and mathematics are best taught by teachers who have chosen to specialise in these subjects.[239, 240, 241] However, subject specialism has yet to be accorded the status it merits. There are still no universally agreed, official UK definitions of a subject specialist science or mathematics teacher at primary, secondary or tertiary level, even though this problem has been identified for a number of years.[242] Definitions of subject specialism would help establish a common nationally applied standard, which would facilitate consistency and accuracy of official counts of subject specialist teachers and confer on them recognition similar to that which clinical consultants in hospitals are accorded.

Definitions should be based on the differing levels of subject knowledge required for teaching at each phase of education and the standard of pedagogical skills required, with these being reflected in the minimum qualifications expected. Notably, the Wellcome Trust's definition of a primary science specialist emphasises the pedagogical skills required, with such teachers needing to: '…have knowledge of an appropriate range of teaching methods suitable for the content concerned. Their knowledge should include enquiry-based pedagogies, practical activities, out-of-classroom learning, group work and problem solving, digital technologies, and formative assessment practices. It should also include an understanding of the key features that result in the successful implementation of these pedagogies and how to evaluate the impact of these on their students.'

The Royal Society of Chemistry (RSC) has suggested a designation for a specialist science subject leader in English primary schools. Its definition considers that a subject leader should:

(i) 'have at least an A-level qualification (or equivalent) in a science, OR undertake extensive training to address any gaps in their subject knowledge;

(ii) AND have obtained Qualified Teacher Status.'[243]

This definition is pragmatic, based on the fact that few primary teachers currently have degree-level qualifications in science (cf. § 5.2.1) and that primary teaching continues to attract few science graduates. On the strength of the RSC's definition, it is reasonable to expect that every primary school in the UK should ideally have, or at least have access to, at least one subject specialist in science and one in mathematics. This is clearly a challenge for the primary sector today – especially in rural areas. But it should be an achievable aspiration for all school leaders.

At secondary level, science and mathematics specialist teachers should be expected to have a relevant degree or experience of their subject through employment or training.[244] It is to be expected that teachers will be qualified in the subjects they teach, and as discussed later in this section, to undertake regular subject-specific professional development.

239 Department for Education 2010, *The case for change*. London: DfE.

240 Science Community Representing Education 2011 *Subject specialist teaching in the sciences: definitions, targets and data*. London: SCORE.

241 Advisory Committee on Mathematics Education 2011 *Mathematical needs. The mathematical needs of learners*. London: ACME.

242 *Op. cit.*, note 226.

243 Royal Society of Chemistry 2014 *Inspiring, engaging and expert: the formula for world-class science and chemistry education*. London: RSC.

244 *Op. cit.*, note 238.

Regrettably, however, the shortages of STEM specialists mean that many teachers have been required to teach outside their subject specialism – for example, biology teachers teaching physics. In this case it is essential that they have access to formal subject-specific professional development from the outset. In England, this option exists currently in the form of Subject Knowledge Enhancement (SKE) course. These courses are valuable as they provide a useful way to support teachers who are required to teach across the sciences, provide a helpful route for those making a career change, or for those returning to teaching after a long absence. SKE has had a particularly positive impact on the subsequent recruitment of its participants to initial teacher education in chemistry as well as in physics.[245]

Science and mathematics specialists should create, lead or implement their school or college's vision for these subjects. Subject-specific professional development is key to supporting school leaders in this endeavour.

5.4 Role of the STEM community in improving the supply of science and mathematics teachers

As discussed in the previous section, there are still no official definitions of a science or mathematics specialist teacher at both primary and secondary level. A role exists here – outlined further in this section - for the UK STEM professional community who have the expertise and experience to advise governments on how best to determine science and mathematics specialism, which would support raising the status of science and mathematics teachers.

Admittedly, there is no 'silver bullet' for resolving the chronic shortages of science and mathematics specialist teachers. Efforts on creating a sufficient workforce should focus on recognising the professionalism of teachers and initiatives designed to widen access to the profession and enhance its appeal to prospective entrants and returners.

It is vital that teaching across the UK should be a confident profession, hallmarked by a culture of self-improvement, excellence and enthusiasm for subject specialism.[246] The STEM community has a particular role to play in supporting this ambition by providing more coordinated leadership, especially in the development of career paths for STEM teaching in all phases of education. Achieving recognised professional status would greatly strengthen the STEM community, and the consequent ripple effect would probably result in increased respect for teaching and teachers in local communities and nationally.

245 Science Community Representing Education 2013 SCORE response to National College for Teaching and Leadership consultation: Pre-ITT Subject Knowledge Enhancement – proposal for 2013/14 and beyond. London: SCORE.

246 House of Commons Children, Schools and Families Committee 2010 *From Baker to Balls: the foundations of the education system*. Ninth report of session, 2009–10. Ref. HC 422. London: The Stationery Office Ltd.

A powerful STEM community coalition will be great than the sum of its parts.

The UK has a unique infrastructure of support for teachers of STEM subjects, funded both privately and publicly. It comprises:

- long-established and well-respected scientific, mathematical and engineering professional bodies. For example, the Institute of Physics (IoP), Royal Society of Chemistry (RSC), Society of Biology (SB); the mathematical societies represented on the Council for Mathematical Sciences, the Royal Academy of Engineering, the 36 professional engineering bodies, Engineering UK and the Engineering Council;
- strong teacher associations (the Association for Science Education, Association of Teachers of Mathematics (ATM), the Mathematical Association (MA) and the Design and Technology Association);
- national centres providing networks for the delivery of professional development the National Science Learning Centre (NSLC) and the National Centre for Excellence in the Teaching of Mathematics (NCETM); and
- a national centre for the co-ordination of resources to support STEM teaching (the National STEM Centre).

It is a powerful coalition whose impact can be greater than the sum of its parts. By building on this infrastructure, it will be possible to create a teaching system in which professionalism is driven from within, as is the case with other professions such as medicine, law and accounting.

Indeed, consultation with the STEM professional bodies and other STEM institutions, including the ASE, NSLC and the NCETM, has indicated interest in increasing their support to teachers to achieve their potential for excellence in STEM teaching. This would include early career development of STEM teachers from their initial teacher education through continuing professional development and on to subject and school leadership.

It would involve STEM specialist teachers being treated as professionals equal to practising scientists, engineers and mathematicians within the STEM institutions. STEM institutions would act to:

- accredit and award professional qualifications for STEM teachers;
- ensure that they have access to regular, high-quality, subject-specific professional development;
- aid best practice in education research and curriculum development;
- provide mentoring and careers awareness through the creation of industry – academic networks;
- provide STEM teachers with better awareness of the career paths that studying STEM subjects can provide for their students; and
- promote professional qualifications among teachers, head teachers and college principals.

Several STEM professional bodies are already engaged in this way: for example, the RSC, the Society of Biology and the ASE are licensed by the Science Council to award Chartered Science Teacher (CSciTeach) status and some secondary school teachers have already gained professional status as Chartered Physicist with the Institute of Physics.

CSciTeach recognises the unique combination of skills, knowledge, understanding and expertise that is required by individuals involved in the practice and advancement of science teaching and learning. It sits alongside other STEM professional qualifications but is as yet largely unrecognised by school and college leaders.

The professional STEM community should support greater understanding and awareness of CSciTeach alongside other qualifications, such as Chartered Mathematics Teacher (CMathTeach), to ensure that STEM teaching is better valued.

For this professional vision to come about, three conditions are necessary. Firstly, the NSLC, the wider network of Science Learning Centres and Partnerships and the NCETM will need long-term investment from Government to enable them to continue to provide quality-assured, subject-specific professional development. Secondly, there needs to be a vote of confidence from Government that these respected institutions can enhance the quality of teaching from the bottom up, in a way that top – down initiatives can never do. Thirdly, head teachers and college principals need to recognise and trust professional qualifications such as CMathTeach and CSciTeach, which requires rigorous quality control by the professional bodies that award them.

5.4.1 Initial teacher education and teacher retention

As § 5.1 suggests, teaching is not a craft that can be learnt simply by on-the-job training; rather it is a profession demanding of specialist knowledge and skills. A comprehensive initial teacher education should develop subject knowledge and a deep understanding of how to teach effectively (Box 16), leading to respected qualifications and the opportunity to enter a career in teaching. However, as in other professions, such as medicine, it is important that teachers who successfully complete their initial teacher education should not be considered the 'finished article' and should commit to ongoing, career-long professional development (see § 5.4.2).

In order to address the existing shortages of science and mathematics specialist teachers, it is important that there should be minimum barriers into initial teacher education, routes back into the profession for those returning from career breaks and flexible ways for professional scientists and engineers to enter teaching at any stage of their career. This mobility should provide a 'two-way street' for all STEM specialists at whatever stage they are in their careers.

For instance, subject specialists (eg chemists or engineers) working in industry should, if they wish, be able to undertake teaching in a local school or college part-time, working towards pedagogical qualifications that complement their subject expertise. This requires a willingness on the part of industry to foster closer ties with schools in their local areas.

This already occurs in Further Education, where schemes exist to enable industry experts to teach part-time. Strengthening the links between vocational training and education in schools and colleges and the learning that happens at work is an important way of ensuring a 'clear line of sight to work' on vocational programmes. Admittedly there are significant challenges in terms of resources, logistics and continuing professional development.[247] 'Teach too', being developed in England, will be designed to encourage more experts from industry to spend some time 'teaching their work' – as part of structured vocational programmes. Such developments to support STEM teaching in colleges are to be encouraged, provided the same rigorous standards of pedagogy and subject specialism and a commitment to continuing professional development apply.

There should be minimum barriers into initial teacher education.

247 Commission on Adult Vocational Teaching and Learning 2013 It's about work… *Excellent adult vocational teaching and learning. Evidence review – Supplementary paper 1.* London: LSIS.

BOX 16

Principles of effective initial teacher education

All initial teacher education courses should be focused on developing deep subject-specialist knowledge and conceptual understanding, and in the context of their specialist knowledge:

- excellent pedagogical skills, including mastery of new technologies;
- a comprehensive set of skills for assessing students' understanding, progress and development;
- substantial practical experience of teaching gained through placements, possibly in both primary and secondary schools, to help them facilitate the transition from primary to secondary education;
- a deep understanding of the sources and consequences of unconscious bias to ensure that achievement in all subjects is high for all pupils irrespective of gender, race or socio-economic background;
- deep knowledge and understanding of educational theory;
- skills in educational research methods;
- familiarity with educational research, building understanding of the importance of keeping up to speed with the latest findings with a view to being able to take advantage of these;
- knowledge of the structure and function of the education system and of the history of education policy reform;
- knowledge of the career pathways open to qualified teachers; and
- confidence to engage with STEM research and industry, both for teachers' own professional development and to ensure that they build the necessary links to provide their students with access to STEM information and careers knowledge.

Innovative approaches to initial teacher education are to be found across the UK. In England, the Government has established over 500 teaching schools. Like teaching hospitals, the network of teaching schools is made up of excellent schools – those which are outstanding in their own performance and have the capacity to support other schools to improve teacher education, professional development and classroom practice.

Similarly, there are other innovative training routes – at Imperial College London (Box 17), Teach First in England and in Scotland, at the University of Stirling, which offers a well-established undergraduate Honours degree in the environment and a primary education teaching qualification. Provided they are properly evaluated to ensure that they work, all of these approaches are a welcome addition to the STEM teacher recruitment landscape.

BOX 17

Studying to be a scientist – and a teacher

The Physics with Science Education three year programme at Imperial College provides students with the opportunity to gain a physics degree and Qualified Teacher Status. It is the first degree of its kind in England and Wales.[248]

Successful students will be awarded a physics degree fully accredited by the Institute of Physics, and will also be qualified to teach science at schools in England and Wales without the need for a further postgraduate qualification. It is a demanding programme, covering 90% of the BSc Physics degree programme; the initial teacher education is provided by Canterbury Christ Church University.

Students take two physics options in their final year as opposed to the usual four. They complete 120 days of teaching practice during the summer before the third year and a further period of teaching practice after their final exams.

In those areas of the UK where shortages of science and mathematics specialist teachers are most acute, more radical action is needed, at least in the short- to medium-term. Wales has plunged in the PISA rankings[249] and has very poor rates of progression of young people to A-level science and mathematics studies.[250] This contrasts with the laudable ambitions of its National Science Strategy. In order to begin to address these issues effectively, and help maximise access to the pool of science specialist and mathematics teaching talent available, there appears to be a case for Welsh medium schools to relax any requirement they may currently have to teach science in Welsh if it becomes clear that there are not enough Welsh medium specialist science and mathematics teachers.

In addition, it is important to recognise that securing a high-quality teaching workforce 'is as much a matter of retention as recruitment'.[251] Indeed with approximately 30% of teacher trainees in mathematics and science subjects not taking up a teaching post in the year following their training,[252] and drop-out within the first five years of entry into the profession being a further cause for concern, school and college leadership teams and subject leaders have a particularly important role to play in supporting beginning and early career teachers (cf. § 3.5.8). There are a number of mechanisms for achieving this, for instance mentoring, participation in external support networks (eg such as Stimulating Physics Support run by the IoP), provisioning of creative and challenging generic and subject-specific professional development, provision of technical support to enable science teachers

248 See http://www3.imperial.ac.uk/ugprospectus/facultiesanddepartments/physics/bscphysicswithscienceeducation, accessed 13 May 2014.

249 Wheater, R, Ager, R, Burge, B & Sizmur, J 2013 *Achievement of 15-year-olds in Wales: PISA 2012 national report*. OECD Programme for International Student Assessment. Slough: NFER.

250 Royal Society 2011 *Preparing for the transfer from school and college science and mathematics education to UK STEM higher education. A 'state of the nation' report*. London: Royal Society.

251 Ev. 7.

252 Ev. 8.

to undertake practical science in addition to offering competitive salaries compared to other graduate professions and good working conditions.[253, 254, 255] Improving staff retention will help build a sufficient and high-quality science and mathematics teaching workforce, which will enhance the stability of teaching teams and the consistency of teaching.[256]

5.4.2 Professional development

ACME has defined professional development as ‘the ongoing education of teachers following the completion of formal initial teacher education to help them develop teaching expertise’,[257] and categorised a set of principles and activities concerning mathematics teachers’ professional development that are equally applicable to science and other subjects (Box 18).

Members of Parliament have observed that the professional development offer available to all teachers in England lacks coherence and focus,[258] but research has established a clear link between excellent, collaborative professional development and improved teaching.[259] It is essential, then, that once they are in post, early career teachers are mentored by their colleagues and subject leaders and supported by the community of professional mathematicians, scientists, engineers and technologists in the sector of research and industry to which they belong.[260]

This kind of development should be experienced through peer-to-peer networking and sharing; technical visits to STEM-related sites; and mentoring provided at school and by business and industry. Such mentoring is already being delivered by leading scientists, as exemplified by the collaborative efforts of the Science Learning Centres (Boxes 19 and 20).

In Scotland, the ambitions of the Donaldson review, published at the end of 2010, were to create a career-long structure of professional development for teachers. As a result, local authorities and universities will together oversee the early part of a teacher’s career and the former Chartered Teacher scheme will be replaced with ‘a system of professional recognition of teachers that demonstrates long term innovative classroom practice’. [261] In addition, the Scottish Government has announced £3 million will be spent over the next 3 years to support Masters level study, a development that could usefully be paralleled elsewhere, for instance by reviving the successful, but short-lived Mathematics Specialist Teacher (MaST) programme (Box 21).

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253 Ev. 7.

254 Ev. 8.

255 Science Learning Centres 2013 *The future of STEM education. A National Science Learning Centre White Paper*. York: National Science Learning Centre.

256 Ev. 8.

257 Advisory Committee on Mathematics Education 2013 *Empowering teachers: success for learners*. London: ACME.

258 House of Commons Education Committee 2012 *Great teachers: attracting, training and retaining the best: Government response to the Committee’s ninth report of session 2010–12*. First special report of session 2012–13. HC 524. London: The Stationery Office Ltd.

259 EPPI-Centre 2003 *The impact of collaborative CPD on classroom teaching and learning. How does collaborative continuing professional development (CPD) for teachers of the 5–16 age range affect teaching and learning?* London: EPPI, Institute of Education. (See http://eppi.ioe.ac.uk/cms/LinkClick.aspx?fileticket=zKuM1BPck20%3D&tabid=135&mid=761, accessed 13 May 2014.)

260 European Commission/EACEA/Eurydice 2013 *Key data on teachers and school leaders in Europe*. 2013 edition. Luxembourg: Publications Office of the European Union.

261 Kidner, C 2012 *Teacher training and employment*. SPICe briefing no. 12/73. Edinburgh: Scottish Parliament. (See http://www.scottish.parliament.uk/ResearchBriefingsAndFactsheets/S4/SB_12-73.pdf, accessed 14 March 2014.)

BOX 18

Principles and activities of professional development

Principles

Professional development that improves mathematics teaching and learning:

- is relevant to the needs of teachers and institutions;
- is mathematics-specific and appropriate to career stage and education phase;
- promotes deep subject knowledge and enhances pedagogical skills;
- is both an entitlement and professional responsibility;
- is sustained and transformative;
- is valued and supported by colleagues, managers and governors;
- is enhanced in professional learning communities and networks;
- is facilitated by experienced and well-qualified experts;
- is informed by research and stimulated by collaborative inquiry groups;
- is planned thoroughly, well-resourced and carefully evaluated; and
- encourages reflection and promotes teacher inquiry.

Activities

Activities that support professional development include:

- critical reflection on, evaluation of, and experimentation in classrooms;
- one-off events, such as training days, INSET, workshops and conferences;
- sustained development opportunities;
- online self-study and other forms of e-learning;
- active engagement in professional development communities and collaborative inquiry groups;
- non-award bearing in-service events run by HEIs [Higher Education Institutions];
- active membership of a subject association;
- courses that develop subject knowledge or focus on classroom practice; and
- postgraduate study such as diploma, Masters or doctoral research.

Source: Advisory Committee on Mathematics Education Empowering teachers: success for learners, 2013

BOX 19

Science Learning Centres and Research Councils UK: bringing cutting-edge science into the classroom

Leading scientists have helped create the professional development available to teachers through the Cutting Edge Science programme. The courses, available in subjects including astrophysics, climate change and nanotechnology, are held across the UK in venues such as the Mill Hill Observatory, Wellcome Institute for Cell Biology and the National Oceanography Centre.

The aim of the programme, organised by the network of Science Learning Centres, is for the scientists to pass on the latest developments to teachers, and for teachers to learn how to teach the curriculum in an accessible, enjoyable and stimulating way. In each course a scientist works alongside a course tutor to explain recent advances and provide an insight into their own current research.[262]

BOX 20

Public and private funders working together

The National Science Learning Centre (NSLC) and National STEM Centre at York are good illustrations of the way that charitable foundations, Government and industry can work together to create an effective infrastructure to support STEM teaching. From an initial grant of £25 million from the Wellcome Trust in 2004, the Centres have since attracted a further £102 million from the Government, the Gatsby Charitable Foundation and a range of industries involved in the ENTHUSE project. ENTHUSE makes it possible for UK teachers of science to attend the NSLC for high-quality professional development at effectively no cost to their school.

Over 70% of secondary schools and 10% of primary schools have now used the NSLC for the professional development of their teachers. Research by the National Audit Office (NAO) regarded the Centre as a very good example of Government support. NAO's research showed that those secondary schools, which had made significant use of the NSLC had student outcomes of 0.5 of a GCSE grade better than schools which had made no or little use of the provision.

262 See https://www.sciencelearningcentres.org.uk/audience/secondary-post-16/cutting-edge-and-contemporary-science/, accessed 13 May 2014.

BOX 21

Developing subject specialist teachers: a lesson from the past to guide the future

The Mathematics Specialist Teacher (MaST) programme was a two year Masters programme of training and professional support that operated in England from 2010 to 2012. The programme aimed to develop the subject knowledge and pedagogical skills of mathematics specialist teachers and their expertise in working with other teachers to improve the standards of mathematics teaching within their schools.

Four cohorts of teachers took part in MaST, working with academics and local authority subject experts. An independent evaluation found the balance between academic learning and practical work had been 'very effective', and that participants were 'highly positive' about the extent to which they had improved their teaching.[263]

Subject-specific professional development should be a requirement for all science and mathematics teachers and linked to recognition and promotion.

Subject-specific professional development should be a requirement for all science and mathematics teachers, with recognition and promotion being contingent on ongoing professional development and proven impact on practice. The UK's inspectorates should seek to commend schools that encourage excellent professional development and that provide teachers time and resources to engage deeply with it (*viz*. part four, Table 4).

There are some notable barriers to making professional development mandatory. Research has found that spending on professional development ranges from 0.25% to 10 – 15% of school budgets,[264] and a report commissioned by the former Training and Development Agency for Schools found that teachers and school leaders did not consider the current range of professional development activities to be always effective.[265] Low levels of science- and mathematics-specific professional development have been recorded among primary teachers, and many courses offered to them are no better than satisfactory.[266] Professional development should encompass engagement with business and industry through mentoring and work placements and time to develop STEM careers awareness. The Primary Science Quality Mark, a scheme designed to raise the profile of the subject in the UK, celebrate excellence and give teachers professional support, has been recognised as being effective at up-skilling primary teachers in this way.[267]

263 NFER and SQW 2013 *Evaluation of the Mathematics Specialist Teacher (MaST) programme. Research report*. London: Department for Education.

264 House of Commons Children, Schools and Families Committee 2010 *Training of teachers, vol. I*. Fourth report of session 2009–10. HC 275-I. London: The Stationery Office Ltd.

265 Storey, A, Banks, F, Cooper, D, Cunningham, P, Ebbutt, D, Fox, A, Morgan, B, Pedder, D & Wolfenden, F 2008 *Schools and continuing professional development (CPD) in England – state of the nation research project (T34718): qualitative research summary*. Cambridge University and The Open University, http://www.teacherdevelopmenttrust.org/wp-content/uploads/2012/05/cpd_stateofthenation_report.pdf

266 Ofsted 2011 *Successful science. An evaluation of science education in England 2007–2010*. Ref. no. 100034. London: Ofsted.

267 Ofsted 2013 *Maintaining curiosity. A survey into science education in schools*. Ref. no. 130135. London: Ofsted.

The UK's principal professional development centres for science and mathematics teachers need long-term funding from Government.

BOX 22

An innovative approach enabling professional development within the working day

At Cramlington Learning Village, a comprehensive school near Newcastle, only two year groups remain in school on Wednesday afternoons. The rest are allowed home for private study and teachers use the time to develop their practice collaboratively in small cross-departmental groups. They share their research findings in an in-house pedagogy magazine called *The Muse*. School leaders organise conferences, and teachers can take part in a virtual CPD programme, with computer software used for lesson observations. All newly qualified teachers take part in a four-year accredited programme, following which they can progress to the middle-management training programme.[268]

Professional development is often only a 'twilight' activity tacked on to the end of the school day.[269] However, this is not the case in all schools, for as Cramlington Learning Village illustrates, there can be time and space in schools for professional development (Box 22).

The UK's principal centres for high-quality, subject-specific professional development for science and mathematics teachers are the National and Regional Science Learning Centres; the Scottish Schools Equipment Research Centre (SSERC); the National Science Academy in Wales, the NCETM (managed by a consortium led by Tribal Education in partnership with the Institute of Education, Mathematics in Education and Industry and Myscience) and the professional STEM bodies and individual subject associations. These kinds of national centres need to be funded by Government over the long-term because they are critical parts of the national infrastructure. In addition, they have the expertise to accredit other local providers to ensure that all teachers can access adequate professional development.

New technologies will make it easier for teachers to benefit from high-quality professional development. Web-supported, blended or distance learning is increasingly available. Examples in mathematics include the Bowland Mathematics Professional Development modules, Massive Open Online Courses (MOOCs), such as Stanford's How to Learn Math, and tutored distance-learning, such as the Open University's CPD modules which support over 700 teachers per year.[270] An online study tool forms part of the Rutherford Schools Physics Project, a five year project funded by the DfE in England and led by Cambridge University academics.

268 See http://www.ofsted.gov.uk/resources/good-practice-resource-consistent-and-innovative-teaching-and-learning-cramlington-learning-village, accessed 13 May 2014.)

269 Ev. 8.

270 *Op. cit.*, note 258.

Finally, and with a view to achieving the objective of giving teachers in the UK much greater responsibility for assessment than they have now (discussed in the previous part), it will be necessary to develop robust teacher appraisal systems to assure and raise standards. Such systems, which are commonplace internationally, would be likely to enhance demand and take-up of professional development opportunities, improve the quality of teaching and the appeal of the profession.[271]

5.4.3 A new College of Teaching

Teaching in the UK currently has no single professional body, but is represented through a range of diverse organisations – from teaching unions and councils to professional bodies and subject-specific teacher associations, such as the ASE, ATM, MA and DATA.

In 2014, the Prince's Teaching Institute launched a blueprint for a College of Teaching, a new member-driven professional body for teachers.[272] MPs on the House of Commons Education Select Committee said a body of this type could play an important role in the 'accreditation of CPD and teacher standards'.[273]

The Royal Society is fully supportive of a stronger and professionally motivated science and mathematics teaching profession and in the previous section set out a vision for how a coalition of STEM institutions can lead the way. Although it is not yet clear how such a College of Teaching could work in England or across the devolved education systems of the UK, the principle of recognising professionalism in teaching is important. Such a body might draw on the work that has already been started by the STEM institutions.

271 *Op. cit.*, note 206.

272 The Prince's Teaching Institute 2014 *A new, member-driven College of Teaching. A blueprint*. London: Princes Teaching Institute.

273 *Op. cit.*, note 259.

OUR VISION

Teachers have high professional status and there is a strong supply of science and mathematics specialists.

Widen access to science and mathematics teaching and enhance the appeal of prospective entrants and returners by expanding the STEM professional community's role in recognising professionalism in teaching.

RECOMMENDATIONS

- Require all school and college teachers to work towards a suitable teaching qualification to ensure they are experts in teaching as well as in their specialist subject.
- Retain STEM technicians in schools and colleges on permanent and well-paid contracts.
- Make subject-specific professional development a core requirement for teachers and technicians and link this to career progression.
- Invest over the long term in national infrastructures which provide access to subject-specific professional development for all STEM teachers and technicians.
- Ensure that every primary school has, or has access to, at least one subject specialist teacher in both science and mathematics and that all post-primary science and mathematics lessons are taught by suitably qualified subject specialists.
- Train and reward teachers to engage fully with digital technologies to improve students' experience of, and attainment in, science and mathematics.

Robust teacher appraisal systems are needed to assure and raise standards of teaching.

Part six
Achieving the Vision

Courage, commitment and an unprecedented collaborative effort are needed to bring about profound and long-lasting changes.

Left
The Royal Society Summer Science Exhibition, 2013.

Achieving the Vision

Action is needed now for the UK to maintain its position as a world leader in science and engineering and have an internationally competitive workforce.

This report has proposed some far-reaching changes to the UK's education systems that focus on improving the quality of science and mathematics education. The table in the summary at the front of this report sets out a 20 year timeline over which these changes need to take place.

Achieving this Vision is contingent on a wide range of factors, a number of which have been discussed earlier in this report. In particular, it will require a collective desire, imagination and determination to change, backed by collaborative and supportive relationships between the education community, higher education, the STEM community, Governments, employers and wider society.

The reforms we advocate focus on science and mathematics, in the knowledge that these two subjects are essential to the life chances of all young people, but we are very aware that they have implications for all other subjects. UK citizens should be provided with the best possible education, understanding that this is likely to yield substantial returns to individuals and the economy. Financial investment in science and mathematics education is as important to the UK as investment in major infrastructure projects in areas such as energy or transport.

We believe the Royal Society can play a key role in providing momentum for this Vision. And whilst many of our messages are for Governments and political leaders, our report is also a call to action for the STEM professional community. This community can exert pressure for reform, nurture the needs of learners and champion the role and achievements of a trusted, well-respected and excellent teaching profession. In particular the STEM community will need to:

- work with Governments to form new bodies to oversee changes in curricula and assessment;
- provide professional recognition and development for all specialist science and mathematics teachers and in the UK; and
- support subject-specific educational research.

This Vision has been produced to help encourage transformation of UK science and mathematics education over the next 20 years. Its publication should be viewed as a spur to encourage national debate. Positive action is required, and should be taken soon, if the UK is to remain at the forefront of scientific and technological advances and continue to have an internationally competitive workforce.

Part seven
Appendices

Appendices

Appendix 7.1 Membership: Vision for Science and Mathematics Education Committee

The following Committee was set up to steer the Vision project. Vision Committee members acted in an individual and not a representative capacity, and declared any potential conflicts of interest. Members contributed to the project on the basis of their own expertise and good judgement.

Chair	
Sir Martin Taylor FRS	Warden of Merton College, University of Oxford
Vice-Chair	
Professor Dame Julia Higgins FRS FREng	Former Chair, Advisory Committee for Mathematics Education (ACME) and Senior Research Investigator, Department of Chemical Engineering, Imperial College London
Members	
Professor Jim Al-Khalili OBE	Professor of Physics, Professor of Public Engagement in Science, University of Surrey
Linda-May Bingham	Head teacher, Britannia Village Primary School, London
Professor Sarah-Jayne Blakemore	Royal Society University Research Fellow and Professor of Cognitive Neuroscience at University College London
Professor Sally Brown OBE FRSE	Convener on the RSE Education Committee, The Royal Society of Edinburgh
The Rt Hon Charles Clarke	Former Secretary of State for Education (2002–04)
Professor Raymond Dolan FRS	Director, Wellcome Trust Centre for Neuroimaging
Professor Dame Athene Donald FRS	Former Chair, Education Committee, The Royal Society and Professor of Experimental Physics, University of Cambridge
Michael Gernon (until December 2012)	Principal, The RSA Academy. (Moved to Dubai in December 2012.)
Sir John Holman FRSC (from May 2012)	Emeritus Professor of Chemistry, University of York and Senior Education Advisor, The Wellcome Trust and the Gatsby Charitable Foundation
Sir Tim Hunt FRS	Emeritus Principal Scientist, Cell Cycle Control Laboratory, Cancer Research UK London Research Institute
Dr Ian Jones	Royal Society Shuttleworth Education Research Fellow, Mathematics Education Centre, Loughborough University
Dame Alison Peacock (from December 2012)	Head teacher, The Wroxham School, Hertfordshire
Professor David Phillips CBE FRSC	Professor Emeritus and Former President, Royal Society of Chemistry
Joan Sjøvoll	Head teacher, Framwellgate School, Durham (deceased, January 2013)
David Swinscoe (from December 2012)	Associate Director, STEM Partnerships, City & Islington College, London
Professor Lord Robert Winston Hon. FREng FMedSci	Professor of Science and Society and Emeritus Professor of Fertility Studies, Imperial College London
Professor Alison Wolf CBE (from December 2012)	Sir Roy Griffiths Professor of Public Sector Management, King's College London

Science Policy Centre staff	
Amanda Farris	Senior Policy Adviser (August–December 2013)
Dr Nick Green	Head of Projects
Yasmin Hossain	Policy Adviser (June 2012–May 2013)
Kerra Maddern	Policy Adviser (from August 2013)
David Montagu	Policy Adviser
Lina Munro	Vision Project Assistant (from August 2013)
Louise Pakseresht	Policy Adviser (from April 2013)
Dr Maike Rentel	Stakeholder Engagement Manager (February–July 2013)
Libby Steele	Head of Education (until May 2012)
Juliet Upton	Vision Project Leader (from October 2012)
Nick von Behr	Education Policy Manager (until February 2012)

Appendix 7.2 Methodology of study

Collection of evidence

Evidence gathering for the project took place as follows:

- a formal process, through an initial call for views;
- events on specific themes that arose during the course of the project;
- nine commissioned research studies; and
- a series of meetings and discussions with key stakeholders.

Call for views

An open call for views was issued in January 2012, following the Vision Committee's first meeting, which resulted in 138 responses. All non-confidential respondents are listed below.

CALL FOR VIEWS

Abington Partners
Gary Anderson
Association for Science Education
Association of Mathematics Education Teachers
Bert Barber
T R Bonella
Alison Braddock
British Mycological Society
British Science Association
Careers Research & Advisory Centre
Nessa Carson
City & Guilds
CLEAPSS
David Cumbers
Tom Davies
Catherine Dunn
Eden Global Consultancy
Engineering Professors' Council
Rhiannon Evans
Esther Fidler
Jenny Gage
Jane Giffould
Roger Green
Beth Hawkins
Dr Chris Harrison
Fiona Harris
Elizabeth Hope
S Hunt
Institute of Mathematics and its Applications
Institute of Physics
Howell G Jukes
Professor Chris King
Professor Diana Laurillard
Peter Jan van Leeuwen
Dave Leese
M Lev
Alex Lucas
Professor Rose Luckin
Mathematics and Science Education Research Centre,
University of Southampton
MEI
Chandra Mehta
Myscience.co Limited
Natural History Museum
Carol Nesham
Richard Newbold
Professor Richard Noss
OCR
Sarah Parsons
Geoff Petty
Sue Pope
John Poultney
Steve Price
Phil Ramsden
Dr David Read
RCUK
Janet Ritchie
Dean Rowley
Linda Sinclair
Keith Ross
Royal Statistical Society
Seb Schmoller
SEPNet
Professor Mike Sharples
Professor John Slater
Professor Aaron Sloman
K Smith
Society of Biology
Adam Southwell
Teach First
The Science Council
Dr S Tunnicliffe
Mike Tuke
Laura Turner
UK Deans of Science
UK Mathematics Trust
University of York, Science Education Group
Sally Waugh
Anne Watson
Wellcome Trust
Stephen Williamson
Maulfry Worthington
K. Yeoman

Events

In addition to running an online discussion forum and teachers' survey, a series of events was held. We are very grateful for the contributions of all the chairs, speakers and participants who took part in these events.

EVENTS	
Facilitated discussion with the British Science Association's CREST Youth Panel, Big Bang Fair, London	16 March 2013
'Visions for improving accountability in education'. An expert seminar jointly held with the Wellcome Trust	16 May 2013
'The future of science and mathematics education'. A workshop at the Royal Society	3 June 2013
Teacher workshop, Eden Project, Cornwall (in association with Myscience)	6 June 2013
Teacher workshop, Thinktank, Birmingham (in association with Myscience)	10 June 2013
Teacher workshop, Museum of Science and Industry, Manchester (in association with Myscience)	17 June 2013
Teacher workshop, National Science Learning Centre, York (in association with Myscience)	20 June 2013
'Full STEAM ahead? Fuelling a renaissance in education'. A debate at the Sunday Times Festival of Education, Wellington College	22 June 2013
'Teaching the science of the future'. Debate on the future of science and mathematics education, Association for Science Education, 50th anniversary conference	29 June 2013
Workshop with the Science Community Representing Education (SCORE)	11 July 2013
Workshop with Vision Project commissioned researchers	16 July 2013
Joint Scenario Planning with Scotland Future Forum and the Royal Society of Edinburgh at the Scottish Parliament	11 September 2013
Key stakeholder workshop on the future of mathematics education	4 November 2013
Vision Committee visit to Imperial College's 'Reach Out Laboratory'	6 November 2013
'Stabilising the curriculum to allow true innovation'. A roundtable discussion involving experts in curriculum and assessment as well as government affairs	21 November 2013
Vocational education roundtable in association with City & Guilds, involving representatives from industry, colleges, education and employment bodies	2 December 2013
Roundtable discussion on the current and future role of the STEM professional community within the Royal Society's Vision for science and mathematics education	1 April 2014

Commissioned research studies

In order to ensure that the project was informed by the best possible evidence, nine studies were commissioned, all of which are published online at www.royalsociety.org/vision, together with an overview summary and details of the research questions they sought to address.

Reference in report	Title	Authors
Ev. 1	Accountability and the meaning of 'success' in education systems and STEM subjects	Professor David Reynolds and Professor Anthony Kelly
Ev. 2	Re-envisioning STEM education: curriculum, assessment and integrated, interdisciplinary studies	Dr Andy Howes, Dimitrina Kaneva, David Swanson and Professor Julian Williams
Ev. 3	Student attitudes, engagement and participation in STEM subjects	Professor Judith Bennett, Dr Martin Braund and Rachael Sharpe
Ev. 4	What are the implications of psychology and neuroscience research for STEM teaching and learning?	Dr Paul Howard-Jones and Dr Tim Jay
Ev. 5	What are the implications of psychology and neuroscience research for STEM teaching and learning?	Ms Jo Evershed, Dr Suzanna Forwood and Dr Adam Rutherford
Ev. 6	The impact of technological change on STEM education	Dr Paul Davies, Dr Geoff Kent, Professor Diana Laurillard, Dr Manolis Mavrikis, Professor Richard Noss, Professor Dave Pratt and Dr Sara Price
Ev. 7	The science and mathematics teaching workforce	Professor Alan Smithers and Dr Pamela Robinson
Ev. 8	Report on leadership and workforce issues within UK science and mathematics education	Professor Andrew Tolmie, Brian Creese, Rebecca Nelson, Jonathan Block, Dr Jon Swain, Olga Cara with Professor Peter Earley, Professor Esmé Glauert, Professor Matthew Harrison, Professor Celia Hoyles, Sally Johnson, Dr Ralph Levinson, Professor Dave Pratt and Professor Michael Reiss
Ev. 9	The benefit of STEM skills to individuals, society and the economy	Professor Ian Walker and Dr Yu Zhu

Selection of case studies in the report

Case studies included in this report illustrate themes that are central to the Vision. International case studies are drawn upon with the understanding that being fundamentally different in culture, they are not directly transposable to the UK.

Appendix 7.3 The Vision Committee's Terms of Reference

Remit and aim of the Vision project

The Vision Committee was tasked by the Council of the Royal Society with formulating an evidence-based vision for the essential features of a future world-class, high-performing education system for 5–19 year olds, particularly with respect to science and mathematics, which will ensure the UK has scientifically and mathematically literate citizens as well as sufficient numbers of scientists and mathematicians to help solve the many challenges the world will face in the coming decades.

Key policy areas for consideration

The Vision Committee's enquiries focused on the following areas:

- leadership and ethos;
- teachers and the wider workforce;
- curricula and skills;
- assessment and qualifications;
- infrastructure;
- accountability; and
- importance of science and mathematics education.

Appendix 7.4 Review Panel

This report has been reviewed by an independent panel of experts, before being approved by the Council of the Royal Society. The Review Panel members were not asked to endorse the conclusions or recommendations of the report, but to act as independent referees of its technical content and presentation. Panel members acted in a personal and not an organisational capacity and were asked to declare any potential conflicts of interest. The Royal Society gratefully acknowledges the contribution of the reviewers.

Chair	
Professor John Pethica FRS	Vice-President and Physical Secretary (Lead Officer on Education), Royal Society
Members	
Professor Carlos Frenk FRS	Director, Institute for Computational Cosmology, University of Durham and Member, Royal Society Education Committee
Keir Bloomer	Member, Scotland's 'Curriculum for Excellence' review group and Chair, Court of Queen Margaret University, Edinburgh
Professor Chris Husbands	Director, Institute of Education, London
Frank McLoughlin CBE	Principal, City and Islington College; Chair of UK Government Commission on adult education and vocational pedagogy
Baroness Onora O'Neill FRS	Chair, Equality and Human Rights Commission
Professor Dame Nancy Rothwell FRS	President and Vice-Chancellor, University of Manchester
Sir Adrian Smith FRS	Vice-Chancellor, University of London
Sir Michael Tomlinson	Former Chief Inspector of Schools in England

Appendix 7.5 Acknowledgements

This project would not have been possible without contributions from a range of individuals. In particular, we wish to thank:

Sir Roy Anderson FRS

Sir John Armitt CBE FREng, City & Guilds

Kalmajit Bains, Highgate School

Hannah Baker, The Wellcome Trust

Yvonne Baker, Myscience

Robert Barbour, ACME

Wendy Barnaby

Paul Beaumont, SSERC

Sir David Bell, University of Reading

Professor Derek Bell

Kate Bellingham

Professor Geoffrey Boulton OBE FRS FRSE, University of Edinburgh

Elizabeth Brimble, GTCW

Professor Julia Buckingham, SCORE

Professor Alan Bundy CBE FRS FRSE FREng, University of Edinburgh

Jenifer Burden, The Gatsby Charitable Foundation

Dr Sandra Cairncross, Edinburgh Napier University

Brian Cartwright, Ofsted

Sir Andrew Cubie FRSE, The Goodison Group

Andrew Curry, The Futures Company

Professor Michael Day, University of Roehampton

Jo Evershed, Cauldron Science

Stuart Farmer, ASE

Jonathan Flockton, The Futures Company

James Fothergill, Confederation of Business and Industry

Dr Simon Gallacher

Dr Paul Golby CBE, Engineering UK

Tom Goldman, Department for Education

Professor Colin Graham, University of Edinburgh

Mrs Faustina Graham, Education and Training Inspectorate

Philip Greenish, The Royal Academy of Engineering

Neil Gregory, School for Startups

Mary Griffin, Pearson

Professor Sunetra Gupta, University of Oxford

Professor Ian Haines, UK Deans of Science

Professor Paul Hardacre, Institute of Physics

William Hardie, Royal Society of Edinburgh

Professor Matthew Harrison, Royal Academy of Engineering

Anna Haslam, Shell UK

Martin Hollins

Jason Holt, Holts Group of Companies

Professor Dame Celia Hoyles OBE, Institute of Mathematics and its Applications

Martin Ince

Paul Jackson, Engineering UK

Donald Jarvie, Scotland's Futures Forum

Professor Edgar Jenkins

Professor Stephen Jones FRS, University College London

Vinay Kathotia, The Nuffield Foundation

Vera Kiss, The Futures Company

The Rt Hon. Lord Jim Knight of Weymouth

Dr Hilary Leevers, The Wellcome Trust

Vaughan Lewis, Myscience

Professor Jim Mather

Roger McCune MBE, CCEA

Lynne McClure, University of Cambridge

Professor Peter Main, Institute of Physics

Warwick Mansell

Katherine Mathieson, British Science Association

Richard Meylan, The Royal Society of New Zealand

Dr Riel Miller, UNESCO

Dr Rosalind Mist, ACME

Dr Bill Mitchell, BCS Academy of Computing

David Moody

Nicole Morgan, The Royal Society of Chemistry

Dr Rhys Morgan, Royal Academy of Engineering

The Rt Hon. the Baroness Morris of Yardley

Richard Needham, Association for Science Education

Sir Dick Olver FREng

Professor Sir John O'Reilly FREng

Richard Page-Jones

Dr Robert Parker, The Royal Society of Chemistry

Dr Karen Petrie, Scottish Informatics and Computer Science Alliance

Professor Simon Peyton-Jones, Microsoft Research Centre

Chris Pope, The Prince's Teaching Institute

Dr Sue Pope, University of Manchester

Ben Ramm, Department for Education

Professor David Reynolds CBE FRSA, University of Southampton

Doug Richard

Conor Ryan, The Sutton Trust

Professor Marcus du Sautoy, University of Oxford

Professor Andreas Schleicher, OECD

Dr Frances Saunders, Institute of Physics

Richard Seymour, Seymour Powell

The Rt Hon. the Baroness Shephard of Northwold

Charlie Stripp, NCETM

Andrew Taylor, AQA

Peter Taylor, Goldsmiths' Centre

Gareth Thistle, Shell UK

Nigel Thomas, The Gatsby Charitable Foundation

Peter Thomas, Joint Mathematical Council

Alec Titterton, Wolfram Group

Professor Anthony Tomei

Oli Tomlinson, Paddington Academy

Charles Tracy, Institute of Physics

Sir Mark Walport FRS FMedSci

David Weston, Teacher Development Trust

Professor Julie Williams

Olga Wojtas

Professor Jonathan Wolff, University College London

Conrad Wolfram, Wolfram Group

Zhenyu Wang

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Appendix 7.6 Glossary

ACCAC	Curriculum and Assessment Authority for Wales
ACME	Advisory Committee on Mathematics Education
AELP	Association of Employment and Learning Providers
ALCAB	A-Level Content Advisory Board
A-level	GCE Advanced Level
ARB	Assessment Resource Bank
ASE	Association for Science Education
AS-Level	GCE Advanced Subsidiary level
ATM	Association of Teachers of Mathematics
BCS	British Computer Society
CCEA	Council for the Curriculum, Examinations and Assessment
CfE	Curriculum for Excellence
CMS	Council for the Mathematical Sciences
CMathTeach	Chartered Mathematics Teacher
CPD	Continuing professional development
CSciTeach	Chartered Science Teacher
CST	Council for Science and Technology
DCELLS	Department for Children, Education, Lifelong Learning and Skills
DENI	Department for Education Northern Ireland
DfE	Department for Education
DfES	Department for Education and Skills
D&T	Design and Technology
EEF	Education Endowment Foundation
ETI	Education and Training Inspectorate
FE	Further Education
GCSE	General Certificate of Secondary Education
GDP	Gross domestic product
GTCW	General Teaching Council for Wales
GVA	Gross value added
ICT	Information and Communications Technology
IOE	Institute of Education
IDL	Interdisciplinary learning
IMA	Institute of Mathematics and its Applications
IMechE	Institution of Mechanical Engineers
IoP	Institute of Physics
IT	Information technology
JCQ	Joint Council for Qualifications

LUCID	Langton Ultimate Cosmic Ray Intensity Detector
LUNAR	Langton Universe Astronomical Research
MA	Mathematical Association
MaST	Mathematics Specialist Teacher (programme)
MOOC	Massive Open Online Course
MPC	Monetary Policy Committee
NAO	National Audit Office
NCC	National Curriculum Council
NCCA	National Council for Curriculum and Assessment
NCETM	National Centre for Excellence in the Teaching of Mathematics
NFER	National Foundation for Educational Research
NICE	National Institute for Health and Care Excellence
NSLC	National Science Learning Centre
OECD	Organisation for Economic Co-operation and Development
Ofqual	Office of Qualifications and Examinations Regulation
Ofsted	Office for Standards in Education, Children's Services and Skills
PISA	Programme for International Student Assessment
QCA	Qualifications and Curriculum Authority
QCDA	Qualifications and Curriculum Development Agency
QTS	Qualified teacher Status
RAEng	Royal Academy of Engineering
RSC	Royal Society of Chemistry
RSS	Royal Statistical Society
SCORE	Science Community Representing Education
SCAA	School Curriculum Assessment Authority
SEAC	School Examinations and Assessment Council
SKE	Subject Knowledge Enhancement
SQA	Scottish Qualifications Authority
SSERC	Scottish Schools Equipment Research Centre
STEM	Science, technology, engineering and mathematics
STEMEC	STEM Education Council
TfI	Teachers from Industry
UKForCE	UK Forum for Computing Education
UTC	University Technical College

Appendix 7.7 Student numbers in the UK[274]

Number of pupils in:	England	Wales	Northern Ireland	Scotland
Independent education[275]	580,000	6,500	690	31,000
Primary and secondary state education[276] (all ages excluding preschool)	6,700,000	390,000	310,000	670,000
Further Education including part-time, work- based study or college study (under age 19)	1,200,000	63,000	79,000	11,000

274 Note: figures are rounded to two significant figures and taken from the following sources:

(i) DfE and National Statistics 2013 *Schools, pupils, and their characteristics*, January 2013. SFR 21/2013. (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/207670/Main_text-_SFR21_2013.pdf, accessed 13 May 2014.)

(ii) Department of Education, Northern Ireland 2013/2014 *Schools and pupils in Northern Ireland 1991/92 to 2013/14*. (See http://www.deni.gov.uk/index/32-statisticsandresearch_pg/32-statistics_and_research_statistics_on_education_pg/32_statistics_and_research-numbersofschoolsandpupils_pg/32_statistics_and_research-northernirelandsummarydata_pg.htm, accessed 13 May 2014.)

(iii) Scottish Council of Independent Schools. (See http://www.scis.org.uk/facts-and-statistics/pupil-numbers/, accessed 13 May 2014.)

(iv) National Statistics, Wales 2013 School census results, July 2013. SDR 109/213. (See http://wales.gov.uk/docs/statistics/2013/130711-school-census-results-2013-en.pdf, accessed 13 May 2014.)

(v) Scottish Government 2013 *Summary statistics for schools in Scotland. 2013 edition, no. 4 (amended 11 February 2014)*. Edinburgh: Scottish Government. (See http://www.scotland.gov.uk/Publications/2013/12/4199/downloads#res439969, accessed 13 May 2014.)

275 Ibid. (nos. 1–4). Data for independent schools in England, Northern Ireland and Scotland do not specify if ‘primary’ category includes early years (up to age 5).

276 Including middle, grammar, special and hospital schools but excluding Referral Units.

Appendix 7.8 Education systems in the UK

Framework	England	Wales	Northern Ireland	Scotland
Compulsory primary and secondary schooling (ages)	Primary (5–11) Secondary (11–18) – by 2015	Primary (5–11) Secondary (11–16)	Primary (4–11) Secondary (11–16)	Primary (5–12) Secondary (12–16)
State curriculum	(English) National Curriculum	(Welsh) National Curriculum	Northern Ireland curriculum	Curriculum for Excellence[277]
Bodies setting the curriculum	Department for Education (DfE)	Department for Education and Skills (DfES)	Department of Education (DE) and Council for the Curriculum, Examinations and Assessment (CCEA)	Education Scotland
Written primary assessment	KS1 and 2 SATs (English and mathematics)	National tests in reading and numeracy	Moderated teacher assessment	None
Mainstream secondary qualifications	GCSEs, A-levels	GCSEs and A-levels	GCSEs and A-levels	Scottish Nationals, Highers and Advanced Highers
Bodies responsible for national assessment (excluding examination boards)	Standards and Testing Agency and Ofqual	DfES	CCEA	Scottish Qualifications Authority (SQA)
Mainstream vocational qualifications	NVQs, BTEC, Diplomas, OCR Nationals, Apprenticeships			SVQs, Modern Apprenticeships
School inspectorates	Office for Standards in Education (Ofsted)	Her Majesty's Chief Inspector of Education and Training (Estyn)	Education and Training Inspectorate (ETI)	Education Scotland

277 Until 2016, when new qualifications developed by the Scottish Qualifications Authority (QCA) will be implemented.

Appendix 7.9 Assessment of practical science and mathematics

Methods for assessing practical science

Direct methods of assessing practical science

- Teacher (or other examiner)-based observations of a student during a practical examination.
- Practical examination by which:
  - an examiner listens to and/or watches a video recording of a student performing a practical task.
  - an examiner views an artwork or a product made by a student in Art or Design and Technology or vocational (eg engineering) course.

Indirect methods of assessing practical science

- Oral assessment (viva) in which a student is interviewed by a teacher or teachers (including external moderator for school-leaving examinations) about a project s/he has undertaken.
- Report by a student on an investigation s/he has undertaken using either his or her own data or data s/he has been provided with.
- Report prepared by a student who has undertaken a practical examination exercise.
- Written test under examination conditions that includes questions on practical work a student will have undertaken during his/her course.

Source: adapted from Reiss *et al.* 2012[278]

278 Reiss, M, Abrahams, I & Sharpe, R Improving the assessment of practical work in school science. (See http://www.gatsby.org.uk/~/media/Files/Education/Improving%20the%20assessment%20of%20practical%20work%20in%20school%20science.ashx, accessed 13 November 2013.)

Principles for assessing mathematics[279]

Assessment of high quality should include tasks that:

Reflect the curriculum in a balanced way
Assessment should be based on a balanced set of tasks that, together, provide students with opportunities to show all types of performance that the curriculum goals set out or imply.

Have 'face validity'
Assessment tasks should constitute worthwhile learning activities in their own right. The tasks should be recognizable as problems worth solving – because they are intriguing and/or potentially useful.

Are fit for purpose
The nature of the tasks and scoring should correspond to the purposes of the assessment. Individual tasks should assess students' ability to integrate as mathematical practices their fluency, knowledge, conceptual understanding, and problem solving strategies. These aspects should not be assessed separately.

Are accessible yet challenging
Tasks should be accessible with opportunities to demonstrate both modest and high levels of performance, so the full range of students can show what they can do (as evidenced by high response rates with a wide range of levels of response).

Reward reasoning rather than results
Tasks should elicit chains of reasoning, and cover the phases of problem solving (formulation, manipulation, interpretation, evaluation, communication) even though their entry may be scaffolded with short prompts to ensure access.

Use authentic or 'pure' contexts
Assessment should contain tasks that are 'outward-looking', making connections within mathematics, with other subjects, and to help one to better understand life and the outside world. As in the real world, they may contain insufficient data (where the student makes assumptions and estimates) or redundant data (where the student makes selections). Students may be asked to respond in a given role: eg a designer, planner, commentator, or evaluator. Tasks that use contrived contexts should be avoided.

Provide opportunities for students to make decisions
Tasks should be included that encourage students to select and choose their own methods, allowing them to surprise or delight. Some may be open-ended, permitting a range of possible outcomes.

Are transparent in their demands
Students should be clear what kinds of response will be valued in the assessment.

279 Swann, M & Burkhardt, H 2012 A designer speaks. Designing assessment of performance in mathematics. Educ. Designer 2, 1–41. (See http://www.educationaldesigner.org/ed/volume2/issue5/article19/index.htm, accessed 1 May 2014.)

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- Promoting science and its benefits
- Recognising excellence in science
- Supporting outstanding science
- Providing scientific advice for policy
- Fostering international and global cooperation
- Education and public engagement

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