GOOD PRACTICAL SCIENCE

GATSBY

Cover image: Illustration by Cath Riley

CONTENTS

Appendices and the costing report commissioned from PricewaterhouseCoopers are available to view at www.gatsby.org.uk/GoodPracticalScience

Appendix 1: The Rapid Evidence Assessment; Appendix 2: Report from the preliminary survey; Appendix 3: Reports from the overseas visits; Appendix 4: The school survey; Appendix 5: Contributors and consultees

FOREWORD BY LORD SAINSBURY OF TURVILLE

Settlor of the Gatsby Charitable Foundation

What is it about science that captivates the imagination of young people? For some it is the excitement of ideas, but for many it is their experiences of hands-on experimentation and practical work in the science lab. That is why I have always sought, through my Gatsby Foundation, to give young people the opportunity to experience exciting hands-on experimentation during their school years, when they are discovering what they are good at, and what careers they want to pursue.

> FUNDAMENTALLY, SCIENCE IS A PRACTICAL DISCIPLINE AND, BY UNDERTAKING GOOD PRACTICAL SCIENCE AT SCHOOL, ONE GAINS A SENSE OF WHAT WORKING IN A SCIENCE-RELATED OCCUPATION MIGHT ACTUALLY INVOLVE

The excitement of scientific investigation, I believe, serves two functions. Firstly, exposure to such activities brings to life the theory and underpinning knowledge of many of the most fundamental scientific concepts and is critical in nurturing a life-long interest in science.

Secondly, it provides opportunities to develop skills crucial in science and engineering careers, including precision, accurate measurement, and the mastery of often delicate equipment. It also develops important transferable skills, such as team-work, resilience and analysis. Fundamentally, science is a practical discipline and, by undertaking good practical science at school, one gains a sense of what working in a science-related occupation might actually involve.

In recent years, with the introduction of new science GCSE and A levels there has been an inevitable concern that the focus of schools on practical science could wane. In the light of these changes to external qualifications, Gatsby is currently working with the Wellcome Trust and the Nuffield Foundation on a longitudinal project to monitor any changes that occur in how schools approach practical science. In the interim however, we asked ourselves how best we could help mitigate against any downturn in the level of practical science offered at schools.

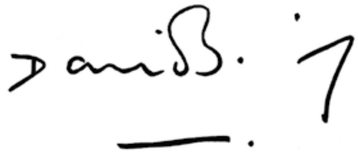
Once again, Gatsby turned to Sir John Holman, long time champion of practical science, and author of our 2014 Good Career Guidance report which set out eight benchmarks for good career guidance in schools and provided a widely-welcomed framework for careers education in England. The challenge to John was simple, though not an easy task: was it possible to develop a framework for good practical science in schools that would be as applicable and helpful as what had been achieved for career guidance?

The short answer was yes. John and the Gatsby team, using a similar model of international visits, surveys and literature reviews, have developed a framework of ten benchmarks that I believe has the appropriate flexibility to make them relevant for all schools in the country.

As with our Good Career Guidance report, the intended audience is not exclusively school leaders or heads of science. There is also a series of recommendations for policymakers and those that can have real influence on the environment within which schools operate. Schools and teachers can only do so much: they do not operate in a vacuum, and I encourage those that can positively impact the system to take note of John's sensible and pragmatic recommendations.

I am not surprised that the research and visits undertaken for this report revealed that where science education is good, practical science is good – that is to say well-planned, frequent and varied. The report also highlights that in terms of equipment and facilities we are relatively well catered for in this country; in most cases a reprioritisation of teaching time could transform for the better the practical science offered to our young people.

Once again, I am extremely grateful to John and all those that have worked with him in producing what I am confident will become another essential tool for schools, teachers and policymakers alike.



David Sainsbury
Settlor

INTRODUCTION FROM JOHN HOLMAN

Experimentation gives science its identity. Science uses experiments to discover the realities underlying the world, and this practical approach seems to be as intrinsic to young learners as it is to professional researchers.

Practical science is important for learning, not only because doing experiments is a good way to learn scientific ideas and theories. The UK needs more scientists, engineers and technicians if our knowledge economy is to flourish, and practical science shows students at first hand how scientists and technicians work. It engages students to follow science further, on academic or technical routes. It gives them practical skills and attitudes that will be valuable in their future careers.

> WE FOUND THAT IN THE COUNTRIES WE VISITED, PRACTICAL SCIENCE IS ALIVE AND FLOURISHING, AND VALUED HIGHLY BY PROFESSIONAL SCIENTISTS, TEACHERS AND, MOST IMPORTANTLY, BY STUDENTS

But at a time when schools in England are under intense pressure to perform in written exams, practical science is at risk. We judge that many schools are making too little use of their often excellent practical science facilities. There is more to learning science than learning how to perform well in exams, important though that is.

We carried out this international study to find out what 'good' looks like in practical science, visiting six countries where science education is highly successful. We found that, in these countries at least, practical science is alive and flourishing, and valued highly by professional scientists, teachers and, most importantly, by students.

Our study has shown that many of the ingredients of good practical science are the ingredients of all good science learning – expert teachers, well-planned lessons and technical support. So, much of what we recommend relates to good science teaching in general. We judge that by world standards, the UK is well equipped with school laboratory facilities, and our benchmarks suggest how to make the best use of them.

I have been supported in this study by experts in six countries:

Professor Harrie Eijkelhof, University of Utrecht, the Netherlands

Professor Jari Lavonen, University of Helsinki, Finland

Professor Knut Neumann, IPN, Kiel, Germany

Dr Graeme Oliver, La Trobe University, Melbourne, Australia

Professor Hannah Sevian, University of Massachusetts, Boston, USA

Associate Professor Ramanathan Subramaniam, Nanyang Technological University, Singapore.

Many other science education experts have contributed to this report: they are identified in Appendix 5. Ginny Page and Beth Jones of the Gatsby Foundation accompanied me on the country visits and contributed significantly to this report.

John Holman

John Holman
September 2017

Sir John Holman is Emeritus Professor of Chemistry at the University of York. He is President of the Royal Society of Chemistry (2016–2018), founding director of the National STEM Learning Centre and a former headteacher and science teacher.

USING THIS REPORT

WE HOPE THIS REPORT WILL BE PARTICULARLY USEFUL TO SCHOOL LEADERS, SCIENCE TEACHERS AND TECHNICIANS, AND ALSO TO TEACHER TRAINERS, POLICYMAKERS, PROFESSIONAL BODIES AND OTHERS WITH A STAKE IN SCIENCE EDUCATION

SCHOOLS

Schools may find section 3, with the 10 benchmarks for good practical science, of particular interest. You can use the criteria in each benchmark to judge how well you measure up against these world-class standards. You will soon realise that many of the ingredients of good practical science are the ingredients of all good science learning.

Section 4 has commentary on the school survey, with a short overview for each benchmark. In Appendix 4 online at www.gatsby.org.uk/GoodPracticalScience you can see the questions we asked when we surveyed a 10% sample of English schools against the benchmarks. Section 5 shows how schools can make progress towards achieving the benchmarks.

For a detailed understanding of the costs involved in meeting the benchmarks, have a look at the costing report from consultants PricewaterhouseCoopers LLP (PwC), which is available online at www.gatsby.org.uk/GoodPracticalScience

School leaders may find the methodology of this costing exercise useful for getting insights into other aspects of your school's costs.

How you use the report will depend on your school and its circumstances. The school survey suggested that science leaders might use it:

- For self-evaluation to underpin continuous improvement.
- For making a business case for changes or improvements in science.
- As a tool to help identify training and development needs for teachers and technicians.

POLICYMAKERS

Policymakers may find sections 4 and 5 and Appendices 4 and 5 useful as a way of judging where we are with practical science in England's schools, and what needs to be done to become world class in practical science. We hope you will look closely at the recommendations.

TEACHER TRAINERS, PROFESSIONAL BODIES AND OTHERS WITH A STAKE IN SCIENCE EDUCATION

Teacher trainers, professional bodies and others with a stake in science education should find the whole report valuable, including the online appendices, as a way of judging what needs to be done to keep practical science as the strong feature of English education that it has traditionally been.

Right: Klosterschule, Germany

EXECUTIVE SUMMARY

HANDS-ON PRACTICAL WORK IS AN ESSENTIAL PART OF LEARNING SCIENCE, IT ALSO DEVELOPS VALUABLE SKILLS AND ATTITUDES AND IS ONE OF THE GATEWAYS TO EMPLOYMENT

WHY PRACTICAL SCIENCE?
SECTION 1

01. This report looks at hands-on practical science in secondary schools and uses an international study to answer the question 'What does good look like?'. The intended audiences for the report are science teachers, school leaders, policymakers, professional bodies and others with a stake in science education.

02. We have found strong consensus around the world, among teachers, students and professional scientists, that hands-on practical work is an essential part of learning science.

03. From our literature review and from a preliminary international survey, we have found a consensus on five purposes for practical science.

04. It is clear from these purposes that policymakers and teachers do not just see practical work as another way of learning scientific theory: it also develops valuable skills and attitudes and is one of the gateways to employment.

05. Practical science prepares students for both technical and general academic study. It motivates students to continue with science whatever path they decide to follow and has the potential to improve the supply of people with scientific skills.

OUR METHOD
SECTION 2

06. We began with a rapid review to find the evidence available on the purposes and impact of practical science. This found that the evidence is limited in both quantity and quality.

07. We surveyed experts in 11 countries to get evidence for the purposes of practical science. From these 11 countries, we chose six which are successful in science education, particularly in terms of the Programme for International Student Assessment (PISA) study.

08. We made in-depth study visits to these six countries: Australia (Victoria), Finland, Germany, the Netherlands, Singapore and the USA (Massachusetts). In each country, we identified at least one science education expert who accompanied us on our visits.

09. We visited a total of 19 schools across these countries and observed lessons, toured the science facilities and talked with students, teachers, technicians, science department leaders and school leaders. We met education officials and academic education specialists.

10. We used these experiences, and our knowledge of UK schools, to draft 10 benchmarks that define the inputs needed for good practical science. We tested these benchmarks in three consultation workshops with UK teachers and science education specialists.

11. Having revised the draft benchmarks, we asked Pye Tait Consulting to survey 10% of English secondary schools against them. We asked consultants PwC to produce a commentary on the costs of implementing each benchmark.

12. We used the benchmarks, the results of the survey, and the costs commentary, to draw up recommendations for government, policymakers, schools and other stakeholders.

THE BENCHMARKS
SECTION 3

13. Our 10 benchmarks for good practical science include criteria to make them measurable, so that schools can see how they are doing against each benchmark. The benchmarks are written from the point of view of schools, because it is school leaders and science heads who make important decisions that affect practical science.

14. The 10 benchmarks are summarised in Table 1. In section 3 we give detailed criteria for each benchmark, and a rationale for why each has been chosen. We give examples drawn from our overseas visits to illustrate the benchmarks.

“OUR 10 BENCHMARKS FOR GOOD PRACTICAL SCIENCE INCLUDE CRITERIA TO MAKE THEM MEASURABLE, SO THAT SCHOOLS CAN SEE HOW THEY ARE DOING AGAINST EACH BENCHMARK”

> EVERY SCHOOL SHOULD HAVE A WRITTEN POLICY THAT EXPLAINS WHY TEACHERS USE PRACTICAL SCIENCE AND THE OUTCOMES THEY EXPECT FROM IT

Table 1: 10 benchmarks for good practical science

Benchmark	Summary	Criteria
1 PLANNED PRACTICAL SCIENCE	Every school should have a written policy that explains why teachers use practical science, the outcomes they expect from it and how they achieve those outcomes. The process of producing the policy is as important as the policy itself.	The policy should be produced as a team effort by teachers and technicians across the science department. The policy should explain the differences in practical science between different age groups. The policy should say how special educational needs and disabilities (SEND) are accommodated. The policy should include any use of opportunities for practical science outside the school, in universities, employers, science centres etc. The policy should be annually reviewed against practice. There should be a member of the senior leader team who will act as a 'sponsor' for practical science among senior leaders.
2 PURPOSEFUL PRACTICAL SCIENCE	Teachers should know the purpose of any practical science activity, and it should be planned and executed so it is effective and integrated with other science learning.	Teachers should have a clear purpose for every practical activity and know how it relates to the rest of what they are teaching. Teachers should plan to their satisfaction how to introduce each practical and how to follow it up. Teachers should take account of students' special educational needs and disabilities (SEND) in their planning, so all students can participate equally.
3 EXPERT TEACHERS	Teachers should have subject-specialist training (both initial and continuing) in the subject (biology, chemistry, physics etc.) and age range they teach, so they can carry out practical science with confidence and knowledge of the underlying principles.	At post-16 level, teachers should have a post-A level science qualification related to the science subject they teach (biology, chemistry, physics), together with relevant pedagogical training. At pre-16 level, if teachers do not have a post-A level science qualification related to the subject they teach, they should have had sufficient additional training to give them the confidence, subject knowledge and skills to conduct effective practical work at that level. School science departments should review their teacher expertise annually, and ensure that individual needs for continuing professional development, including time for professional reflection, are being met. This should include specific training in practical science.
4 FREQUENT AND VARIED PRACTICAL SCIENCE	Students should experience a practical activity in at least half of their science lessons. These activities can be short or long, but should be varied in type.	On average, across the year and across all the sciences, at least half of lessons should involve direct practical activities, whether hands-on or teacher demonstration. Practical activities can be short or long. There should be enough long science lessons (of at least 50 minutes) in the timetable to give teachers flexibility about when they do experiments. Practical activities should be varied and balanced in type (see section 1.6).

Benchmark	Summary	Criteria
5 LABORATORY FACILITIES AND EQUIPMENT	Schools should have enough laboratories to make it possible for every teacher to do frequent practical science safely. Each laboratory should have sufficient equipment for students to work in small groups.	☐ There should be enough laboratories so that the availability of labs is never a barrier to carrying out practical activities in the science subjects taught. ☐ Laboratories should be large enough to safely accommodate the size of classes that will occupy them. ☐ The spaces should be flexible enough to allow students to work individually, in pairs and in small groups. ☐ There should be sufficient equipment to make it possible for teachers to do standard practical activities expected in their specialist subject at that level. ☐ There should be ready access to the technology required to enable collection and analysis of digital data. ☐ Laboratories should be accessible to students with any special educational needs and disabilities (SEND) encountered in the school. ☐ The school should have laboratory facilities such that students can carry out extended practical science investigations (see Benchmark 8). ☐ There should be a preparation space or spaces with well-organised, safe storage with easy access to laboratories. ☐ There should be an accessible outdoor space where practical activities can take place.
6 TECHNICAL SUPPORT	Science departments should have enough technical or technician support to enable teachers to carry out frequent and effective practical science.	☐ For an average-size school, there should be specialist technical expertise to support practical work in each of biology, chemistry and physics. ☐ Technicians should be given regular opportunities to have professional development.
7 REAL EXPERIMENTS, VIRTUAL ENHANCEMENTS	Teachers should use digital technologies to support and enhance practical experience, but not to replace it.	☐ Virtual environments and simulated experiments have a positive role to play in science education but should not be used to replace a good quality, hands-on practical. ☐ Digital technologies are rapidly evolving and teachers should have access to evidence about what works, and training in their use, before implementing them in their science lessons.
8 INVESTIGATIVE PROJECTS	Students should have opportunities to do open-ended and extended investigative projects.	☐ There should be opportunities for students to do open-ended extended investigative projects in science. ☐ The school should have laboratory facilities such that all students who want to can carry out extended practical science, particularly among post-16 year olds.
9 A BALANCED APPROACH TO RISK	Students' experience of practical science should not be restricted by unnecessary risk aversion.	☐ Responsibility for safety is shared between the school or local authority as employer, the teacher and the technician. This should be clearly understood by all members of science staff. ☐ The school should ensure that teachers and technicians have access to authoritative and up-to-date guidance including model risk assessments. ☐ Teachers should assess the risks and benefits for every practical activity, and act accordingly. ☐ Teachers and technicians should adopt a balanced and proportionate approach to managing risks, and be supported by senior management in doing so.
10 ASSESSMENT FIT FOR PURPOSE	Assessment of students' work in science should include assessment of their practical knowledge, skills and behaviours. This applies to both formative and summative assessment.	☐ Teachers should reflect on students' practical skills and knowledge when awarding a grade for science. ☐ Teachers should regularly use practical activities as an opportunity to formatively assess students' understanding of science, where it is appropriate to do so.

> OVERALL ENGLISH SCHOOLS ARE WELL PROVIDED WITH LABORATORY FACILITIES, SO IT IS DISAPPOINTING THAT MANY SCHOOLS ARE NOT MAKING FULL USE OF THEM

THE SCHOOL SURVEY
SECTION 4

15. The school survey involved about 10% of English secondary schools with a cross-section of school types, sizes and regions. The questions in the survey were derived from the benchmarks, and enabled us to measure schools against them. The survey was followed up by qualitative interviews with 20 schools, again a cross-section.

16. Meeting all the criteria for all the benchmarks is demanding, and the survey confirms that most schools fall well short of achieving world-class practical science measured in this way. Just over a third achieved none of the benchmarks, and no school reaches more than seven full benchmarks. But the detailed analysis of benchmark criteria shows that many schools are well on their way to achieving them.

17. Notably, it looks as if most schools in England are falling well short of the recommended frequency for practical science in Benchmark 4, and that this is particularly true for older students taking examined courses.

18. We judge that, by international standards, overall English schools are well provided with laboratory facilities, so it is disappointing that many schools are not making full use of them.

MAKING PROGRESS TOWARDS THE BENCHMARKS
SECTION 5

19. PwC used the Standard Cost Model to estimate the costs of each benchmark. This involved using activity-based costing to break down each benchmark into its component activities.

20. The costing exercise confirms that by far the greatest part of the cost of practical science is staff time – the large majority being teachers' time. The capital costs of laboratories and equipment are small by comparison. The school is already paying the salaries of teachers, and if they were not doing practical science they would be doing some other kind of learning activity.

21. We include for each benchmark a commentary on the costing analysis.

22. We believe that a school's progress in improving practical science can best be made by prioritising Benchmarks 1 (Planned practical science), 3 (Expert teachers) and 6 (Technical support), because these three benchmarks are strong enablers for others.

RECOMMENDATIONS
SECTION 6

23. Our 10 recommendations are presented in detail in section 6 and summarised in Table 2 on the opposite page.

24. We recommend Benchmarks 1–10 as defining the elements of good practical science in secondary schools. They should guide schools and help teacher trainers and professional development leaders to shape their programmes. Ofsted should guide schools towards them if their science needs improvement.

We have recommendations about:

25. What government and policymakers can do to secure and maintain:
    - The supply of expert teachers.
    - A system that recruits and develops expert teachers.
    - A curriculum, assessment and accountability system that encourages good teaching.

26. What schools can do by:
    - Investing in expert people.
    - Planning for practical science.

Table 2: Summary of recommendations

Recommendations for all | Recommendations for government and policymakers | Recommendations for school leaders and member bodies

1 THE 10 BENCHMARKS	To schools, policymakers, Ofsted and teacher trainers	We recommend Benchmarks 1–10 as defining the elements of good practical science in secondary schools. Schools should use them, policymakers should be guided by them, and teacher trainers and professional development leaders should use them to help shape their programmes. Ofsted should guide schools towards them if their science needs improvement. Schools, and the science departments within them, should be funded adequately to enable them to achieve the benchmarks.
2 TRAINING EXPERT TEACHERS	To government and teacher trainers	Secondary science initial teacher training (ITT) should have a strong subject-specific component relating to the science they will teach, especially its practical aspects. This should be reflected in the standards for Qualified Teacher Status (QTS), which should apply to teachers in all state-funded schools, including academies. Government-funded Subject Knowledge Enhancement (SKE) courses for prospective science teachers should include sufficient laboratory time to develop practical skills. Courses that are only delivered online cannot provide this experience. Government should ensure that the Teacher Supply Model (TSM) accurately forecasts the number of specialist teachers required. Government should use the TSM to increase the number of specialist teachers in each of the sciences, through additional recruitment and through retention programmes, so that schools have enough high-quality applicants when they advertise posts.
3 CONTINUING PROFESSIONAL DEVELOPMENT FOR TEACHERS	To government, teaching unions, professional bodies and other stakeholders	Over the next five years, England should move towards an embedded system of continuing professional development (CPD) for teachers, with clear expectations of quantity and quality of CPD. Teachers' CPD should have a strong subject-specific focus and in the case of science teachers it should include practical work wherever appropriate.
4 ACCOUNTABILITY AND PRACTICAL SCIENCE	To government	Government should review accountability measures compared with other nations, to assess how they could give teachers more autonomy and freedom to innovate in the way they teach, particularly in the case of practical science.
	To Ofsted	When inspecting school science departments, Ofsted should take particular note of the quality and frequency of practical science, and record it in the report on the school.
5 VALID ASSESSMENT	To government and Ofqual	Government and Ofqual should monitor current arrangements for assessment of practical science at GCSE and A level to check their impact on the quality and frequency of practical science. If negative effects are found, changes should be made.
	To research funders	Research should be done into valid, reliable and manageable ways of assessing practical science, in particular where assessment is indirect and by means of written questions.
6 PROJECTS IN THE CURRICULUM	To government and Ofqual	The curriculum should evolve to include more requirements for extended projects in investigative science. In particular, an extended project should become an embedded, compulsory part of post-16 study for all students on pre-university courses. For those studying a majority of science subjects, the project should have a science focus.
7 RECRUITING, RETAINING AND DEPLOYING SPECIALIST TEACHERS	To school governors, headteachers and science leaders	Schools should take a strategic approach, using a combination of shrewd recruitment, retention measures and CPD, to get a better proportion of science subject specialists in their science team. Where subject specialists are scarce, they should teach within their specialism where possible, and schools should take a strategic approach to deciding which classes and age groups to use them with.
	To science professional bodies and funders	A study should be commissioned to produce practical recommendations for schools on how to achieve the above. The result of this study would be a practical guide for schools, illustrated with case studies, on how they can get a better proportion of science subject specialists, and how best to deploy them.
8 VALUING SCIENCE TECHNICIANS	To school governors, headteachers and science leaders	Technicians should be valued as an integral part of the science department. They should be given professional development opportunities to refresh their professional skills and their expertise in health and safety, and to give them new ideas for practical science. They should have opportunities to get professional recognition through Registered Science Technician (RSciTech) and Registered Scientist (RSci).
9 PLANNING FOR SUCCESS	To the Association for Science Education and science professional bodies	Drawing on the experience of schools, guidance should be produced on how to go about developing a written policy for practical science.
10 MANAGING RISKS	To school governors, headteachers and science leaders	All schools in England should belong to CLEAPSS, either individually or through their local authority or Academy Trust, and should use its expert advice to ensure a balanced approach to risk.

1

WHY PRACTICAL SCIENCE?

WE HAVE FOUND THAT, DESPITE THE GROWING POWER OF DIGITAL TECHNOLOGY TO SIMULATE THE REAL WORLD, PRACTICAL SCIENCE IS AS HIGHLY VALUED AS EVER

1.1 WHY A REPORT ON GOOD PRACTICAL SCIENCE?

All over the world, hands-on practical work is seen as a vital part of learning science, just as speaking and discussion are a vital part of learning languages. This consensus is found among teachers, students, parents, employers and professional scientists. We have found that, despite the growing power of digital technology to simulate the real world, practical science is as highly valued as ever.

This report is about practical work in science education, and it asks the question 'What does practical science look like when it is good?'. When we searched the literature (section 1.3), we found remarkably little published evidence on the impact of practical science, and this was one of our motivations for undertaking an international study.

Professional scientists are vociferous in their long-standing support of practical science – and sometimes critical. In a 2011 survey,[1] 97% of lab managers in Russell Group universities reported that incoming undergraduates are poorly equipped for first year practical science. In the majority of cases they said this situation had declined over the past five years, more so than declines in knowledge and understanding.

The Gatsby Foundation is one of many organisations to support practical science. The Royal Society, the UK's national academy of science, emphasises that practical work is integral to science and should not be seen as an 'additional component' of teaching and learning.[2] The largest scientific professional bodies (The Royal Society of Biology, Royal Society of Chemistry and Institute of Physics),[3] the Wellcome Trust and the Association for Science Education (ASE)[4] are strong supporters of practical science and we have been able to draw on their findings in this report.

1.2 THE PURPOSES OF PRACTICAL SCIENCE

Enthusiasm for practical science is all very well, but we wanted to know why teachers and policymakers think it is so important. What benefits come from practical science that don't come from other ways of teaching? In other words, what are the *purposes* of practical science?

This is an important question because if you want to know what 'good' practical science looks like, you need to know what outcomes are expected. We realised that the *intended* purposes of practicals (as conveyed by official curriculum documents) might not be the same as the *actual* purposes in teachers' minds.

Our preliminary survey

Section 2 describes the overall methodology for our study. At the beginning, we identified expert witnesses in 11 countries where science education was known to be effective, as judged by, among other things, the Programme for International Student Assessment (PISA 2012).[5] The 11 countries were: Australia (Victoria); Canada (Ontario); Finland; France; Germany; Japan; The Netherlands; New Zealand; Singapore; Switzerland, and the USA (Massachusetts).

Box 1: The purposes of practical science (not in any order of priority)

A
TO TEACH THE PRINCIPLES OF SCIENTIFIC INQUIRY

B
TO IMPROVE UNDERSTANDING OF THEORY THROUGH PRACTICAL EXPERIENCE

C
TO TEACH SPECIFIC PRACTICAL SKILLS, SUCH AS MEASUREMENT AND OBSERVATION, THAT MAY BE USEFUL IN FUTURE STUDY OR EMPLOYMENT

D
TO MOTIVATE AND ENGAGE STUDENTS

E
TO DEVELOP HIGHER LEVEL SKILLS AND ATTRIBUTES SUCH AS COMMUNICATION, TEAMWORK AND PERSEVERANCE

We asked the experts to tell us the formally intended purposes of practical science in their country, as described in official documents. We also asked them for their view on how teachers actually interpret the purposes.

The report from this preliminary survey is in Appendix 2. We found a good consensus for the five purposes identified in the box, and this consensus was confirmed by the Rapid Evidence Assessment (section 1.3). We have used these five purposes as the basis for our report.

It is clear from these results that policymakers and teachers do not just see practical work as another way of learning scientific theory: it develops valuable skills and attitudes and is one of the gateways to employment.

Another important finding from this preliminary survey was that *teachers do not always interpret the purposes of practical science in the same way as official documents*. In particular:

– Teachers tend to value the motivational purpose of practical science (D) more highly than other purposes.

– They tend to rate less highly the use of practical science to teach the principles of scientific inquiry (A) and specific practical skills (C).

– Teachers say that in reality, what is intended to be scientific inquiry may be limited to following a set of instructions.

1.3 THE EVIDENCE AROUND THESE PURPOSES

This study has been informed and influenced by the work of respected researchers and in particular by the contributors to the Association for Science Education's *Getting Practical*[6] project. At the start of this study, we wanted to augment such work by reviewing the international evidence around the purposes of practical science and how well it delivers on these purposes. We commissioned a Rapid Evidence Assessment (REA) from the Institute for Effective Education in York, the full report of which is in Appendix 1.

The REA found that, among the research published in English, there are few studies with a well-defined focus on practical science. Below we summarise the evidence against each purpose, but it is important to note that not all the studies are considered methodologically robust, and that many are relatively small in scale. Details of the studies referred to are in Appendix 1.

A. To teach the principles of scientific inquiry

The REA found five studies showing a positive effect and one showing no effect.

In addition, the PISA 2015[7] study (which *is* considered methodologically robust), found a positive correlation between strong epistemic knowledge[8] about science (which roughly translates as 'thinking scientifically') and 'inquiry-based instruction'.[9] In other words, PISA finds that doing practical science correlates with having a scientific attitude of mind.

B. To improve understanding of theory through practical experience

The REA found five studies showing a positive effect and five finding no effect.

In addition, the PISA 2015 study found a negative correlation between performance on the PISA science tests and 'inquiry-based instruction'. This confirms a fact that will be familiar to teachers: practical activities are not necessarily the most efficient way of preparing students for written tests.

Above: Damstede School, the Netherlands

C. To teach specific practical skills

The REA found two studies showing a positive effect, one of which was considered to be methodologically weak.

D. To motivate and engage students

The REA found four studies showing a positive effect. In addition, PISA 2015 and Wellcome's Science Education Tracker,[10] published after the REA was carried out, both provide robust evidence of a positive effect. We deal with this evidence in more detail in section 1.4.

Any science teacher will confirm that students are motivated and engaged by practical science, and this impression is backed up by the most robust evidence we have found around the impact of practical science.

E. To develop higher level skills and attributes

The REA found one study showing a positive effect.

The box to the right gives some of the answers we got when we asked teachers and students why practical science is important. These examples illustrate that practical science has outcomes beyond the formal ones stated in official curriculum documents.

WHY DO PRACTICAL SCIENCE?

"To create a shared experience. Students arrive in the classroom with very different sets of home experiences, but an experiment creates a level playing field for discussion and reflection."
Teacher in Massachusetts

"For students with poor English, practical work is a way to reinforce learning through concrete experiences."
Teacher in a multilingual school in Australia

"Students gain respect for nature by working with living organisms in practical biology."
Teacher in Germany

"It helps you understand theory by creating a link to real life."
Student in the Netherlands

"It's the unexpected things that happen. We did an experiment to get pure water by distilling cola, but the amazing thing was the gunk that was left behind."
Student in Australia

"I mixed lead nitrate solution with potassium iodide solution. I knew it would turn yellow, but I didn't expect the weird streaks."
Student in Australia

"We are more confident about what we know when we have found things out for ourselves."
Student in Germany

1.4 PRACTICAL SCIENCE AND PROGRESSION WITH STEM

Students find practical science engaging (see below), and that matters. If a student engages with a subject, they are more likely to apply themselves to learning it and to continue studying it. With the present and projected shortages of people with science, technology, engineering and mathematics (STEM) skills in the UK, enjoying science and wanting to continue with it are as important as getting good marks.

Wellcome's Science Education Tracker is a survey of 4,081 young people in schools in England, aged 14–18, which was carried out in 2016. Students were asked about their experiences of studying science in school.

When Wellcome asked students about the reasons for enjoying science at school, the leading factors turned out to be having a good teacher and enjoying practical work. In both cases, 35% of students said this had encouraged them. Given what is already known about the critical role of teachers, this is a strong vote in favour of practical work. The data also shows a connection between a teacher being seen as 'good' and the amount of practical work that teacher does.

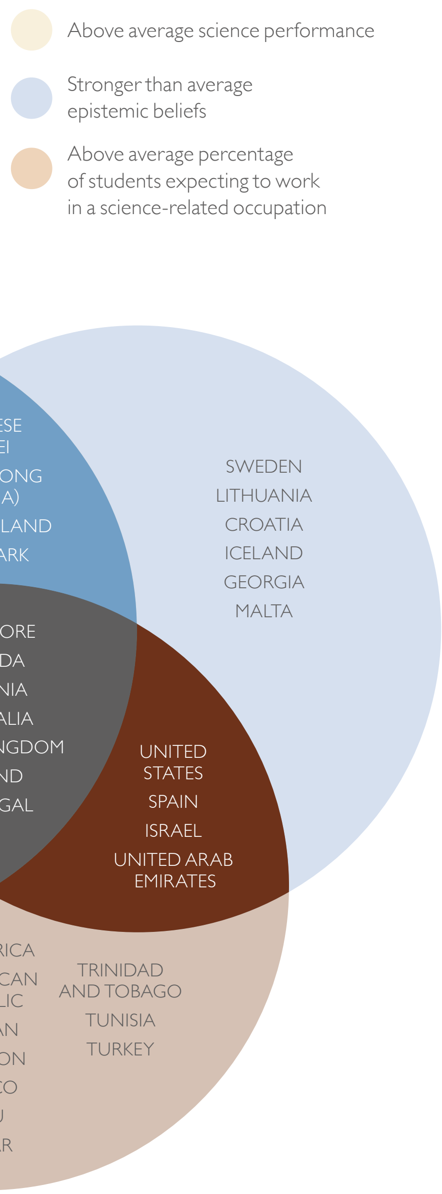
Students with low family science connections[11] were more likely to want to do more practical science. However, the Tracker found that children from deprived backgrounds[12] were actually *less* likely to have done higher level practical science in school. This suggests that increasing the opportunities for such students to do practical work could engage them more with science – which is important because on average they are less likely to choose to continue science beyond school. The ASPIRES project finds that a key factor affecting the likelihood of a student aspiring to a science-related career by the age of 14 is the student's amount of 'science capital'.[13]

PISA 2015 showed the UK as one of only seven countries (out of 72) that showed above-average achievement in science, above-average science epistemic knowledge[14] *and* above-average interest in a scientific career (Figure 1). Performance in science tests does not correlate with practical science, but science epistemic beliefs and interest in science do. Practical science may not be the most efficient way to prepare for written tests, but it develops scientific attitudes and it builds interest in science as a career.

Practical science prepares students for technical education routes as well as for general academic study. It motivates students to continue with STEM whether they are heading for university, a technical qualification or a STEM apprenticeship. The hands-on aspect of science shows students that science is a practical subject that involves much more than abstract thought alone, and it develops physical skills as well as cognitive ones. The UK economy needs people with STEM skills at all levels, from technicians to PhDs, and practical science engages and motivates people towards all these destinations.

> "EXPERIMENTS DO NOT ALWAYS GO AS EXPECTED, AND WE CAN LEARN AS MUCH FROM UNEXPECTED RESULTS AS FROM EXPECTED ONES"

Figure 1: Seven countries scored above average in three dimensions in PISA 2015



> EXPERIMENTATION GIVES SCIENCE ITS IDENTITY. SCIENCE USES EXPERIMENTS TO DISCOVER THE REALITIES OF THE WORLD, AND THIS PRACTICAL APPROACH SEEMS TO BE AS INTRINSIC TO YOUNG LEARNERS AS IT IS TO PROFESSIONAL RESEARCHERS

Our conclusion to the question 'Why practical science?' is that the answer is more nuanced than the five purposes we identified in our surveys. Experimentation gives science its identity. Science uses experiments to discover the realities of the world, and this practical approach seems to be as intrinsic to young learners as it is to professional researchers. The attraction of practical science seems to lie in its appeal to the senses, its surprises and its unpredictability, as much as in its power to explain. The real world is not cut and dried, and nor is practical science. Experiments do not always go as expected, and we can learn as much from unexpected results as from expected ones. And the same is true of life.

1.5 THE SCOPE OF THIS REPORT

For the purposes of this report:

Science education includes biology, chemistry, physics, combined science, earth science, and other experimental sciences but excludes mathematics, engineering, design and technology, computer science and social sciences.

Educational institutions include secondary schools and sixth form colleges, whether maintained and controlled by a local authority, an academy trust or independent. Primary schools and further education colleges are outside the scope of the study, though practical science is important in both.

We are interested in secondary schools across all four UK nations, but particularly in England, where 84% of the UK population live. The school survey (section 4) looked only at schools in England, and our policy recommendations (section 6) relate to England.

Practical science describes a wide variety of activities in which students manipulate and observe real objects and materials in laboratories and field studies, but it excludes:

- The manipulation of data that has not been collected by students themselves.
- Visits to places of scientific interest when no fieldwork or hands-on activity takes place.

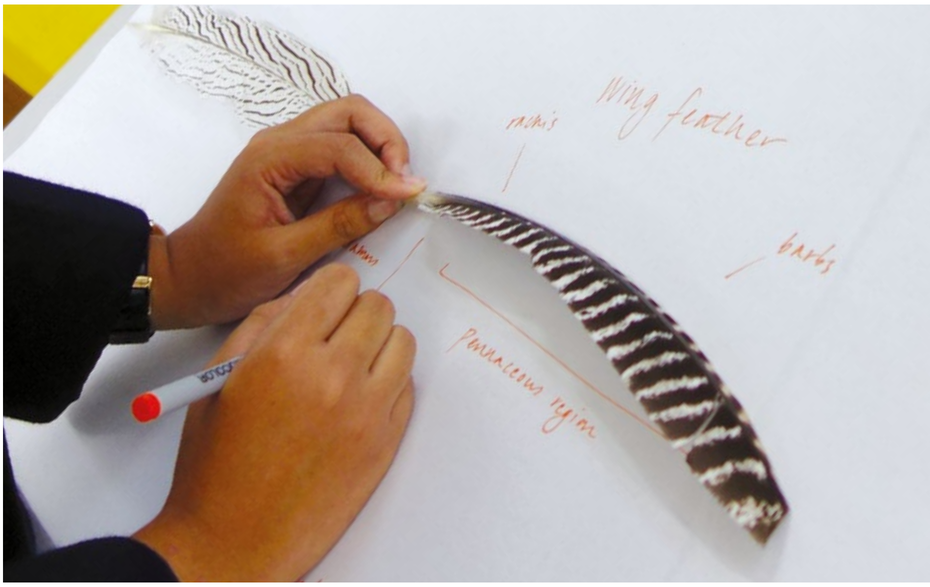
We are not saying that there is no educational value in these activities, just that they are outside the scope of this report.

Practical demonstrations by teachers, where they actively involve students, are within the scope of the report.

1.6 TYPES OF PRACTICAL SCIENCE

We found at the beginning of our study that practical science has a range of purposes (section 1.2), so we might expect to find a range of types of practical activity. This is indeed what we discovered in our visits: there are many different ways to do successful practical science. Some of the most effective activities we saw were very short, but we also saw extended science projects that took weeks, not days. Some activities were designed to confirm a theory that students had already learned about; others were designed to introduce a theory for the first time. Some were intended to teach a particular skill such as using a microscope. There is no single, best type of practical activity: the important thing is that the teacher knows why they are doing it and has carefully planned how to introduce it and follow it up.

Below: Studying feathers at Penleigh and Essendon Grammar School, Australia



WHAT DO TEACHERS LOOK FOR IN A PRACTICAL ACTIVITY?

A successful and experienced physics teacher in Finland told us that her ideal practical activity:

– Uses simple equipment and is accessible to all students.

– Is straightforward to carry out.

– Raises interesting questions for discussion afterwards.

A highly experienced chemistry teacher in Massachusetts confided: "Most of the experiments I do are designed to confirm theories I've already taught. I use the activity to reinforce the theory and also to introduce scientific processes and skills such as data handling."

Right: Making a boomerang to study aerodynamics at Penleigh and Essendon Grammar School, Australia

There is no definitive way to define the different types of practical science, though there have been notable attempts.[15, 16] The following typology is derived from what we saw in our visits to schools overseas and in the UK. The types are not mutually exclusive: a given practical activity may be of more than one type. These activities would normally be done by the students themselves, but they may in some cases be teacher demonstrations.

As far as duration is concerned, we define short activities as taking less than one lesson; standard as one lesson (where a lesson lasts an hour); long as up to one week (where one week has three or four lessons); extended as more than one week.

The most common types of activity we saw are listed below (not in any particular order):

Confirmatory experiments, in which students do an experiment designed to confirm or apply a theory they have already met. These are often of short or standard duration. For example, in Massachusetts we saw pre-university students using conservation of momentum to predict the behaviour of dynamics trolleys.

Experiments to derive theories, in which students carry out experiments designed to reveal a theory. These are often of short or standard duration. For example, in Finland we saw students using laser pointers and glass blocks to derive Snell's Law of refraction.

Technique development, in which students learn or develop a particular scientific technique. These can be of short or standard duration. For example, in Singapore we saw students practising their technique in titrations.

Observation activities, in which students practice scientific observation. These are often of short or standard duration. For example, in Australia we saw students observing and classifying different types of birds' feathers.

Investigations, in which students design an experiment to test a given question, carry it out and interpret the results, all within a fixed time period. These may be of standard or longer duration. For example, we saw students in Germany using a classic experiment to investigate the relationship between voltage and current in an electric circuit.

Projects, in which students think of a question, design an experiment to test it, carry it out and interpret the results, within an extended time period. For example, in the Netherlands we saw two pre-university students analysing the harmonics of the human voice to see if they correlate with ethnicity. Projects may involve collaborative research, in which students work as part of a group investigating a research question over an extended time period, often supported by a researcher from university or industry. For example, in Singapore we heard about students who were working with a scientist in residence to measure the quality of the water running off green roofs.

Practical science does not always have to be done in a laboratory. A few activities can be done in a classroom or a corridor, and access to an outdoor pond and garden are essential for biology teaching. Fieldwork in locations outside school is harder to organise but is particularly important for post-16 biology courses. At Nöykkiö school in Finland, in a semi-rural location near the Baltic Sea and forests, all Grade 8 students did a forest biology project, carrying out small studies over the course of three-hour trips.

2

THE SEARCH FOR 'GOOD'

WE NEEDED TO LOOK FURTHER, AND TO SEE FOR OURSELVES WHAT 'GOOD' LOOKS LIKE IN PRACTICE

2.1 SUMMARY OF OUR METHODOLOGY

An obvious way to find out what 'good' looks like in practical science would be to comb the research literature. But the Rapid Evidence Assessment (section 1.3) confirmed that there are few studies with a well-defined focus on practical science and a robust research design. We needed to look further, and to see for ourselves what 'good' looks like in practice. We used an international comparative method similar to an earlier successful study of Good Career Guidance.[17] The main elements of our method are in Figure 2.

2.2 LOOKING OVERSEAS

We already knew that by world standards the UK is well equipped with laboratory facilities. PISA 2015[18] confirms that headteachers in the UK are more positive about their school's resources for science teaching than in the average high-performing country. Add to this the well above-average technician support (by international standards), and we have a picture of the UK being well set up for practical science. But are we making the most of our advantages? What are the other ingredients for good practical science? And does practical science have other positive outcomes as well as preparing students for exams? These are the questions that prompted us to look overseas.

Our *preliminary survey* of 11 countries is described in section 1.2. From it, we selected six countries[19] for the *international visits*. We selected countries that we knew from international comparisons such as PISA and TIMSS to be successful in science education, and where our preliminary survey had identified an expert witness who would be well placed to help us organise and inform our visits. These expert witnesses were both knowledgeable about science education in their country, and independent enough to give an objective view. Typically, they were university academics specialising in science education: their names are in the Introduction on page 7.

From these six in-depth visits, we have made professional judgements, in light of our own knowledge of UK schools, about the elements of good practical science. These judgements are the basis for the 10 benchmarks in section 3.

The six countries we selected to visit are listed below. Detailed reports from each visit are in Appendix 3.

- Australia (Victoria), chosen for its success in science education and its cultural similarity to the UK. We visited four secondary schools in the greater Melbourne area (one being independent, the others state-funded) and two science centres.
- Finland, chosen because of its consistently successful science education and the similarity of its comprehensive system to the comprehensive norm in the UK. We visited three schools in the Helsinki region and met teachers and officials at the Finnish National Board of Education.
- Germany, chosen for its success in science education. We visited three academic secondary schools (gymnasia) in the Hamburg and Kiel region and met teachers and science education researchers.
- The Netherlands, chosen for its successful science education and its cultural similarity to the UK. We visited three general academic schools (VWO and HAVO)[20] in Amsterdam and Utrecht and had a workshop with teacher trainers in Amsterdam.
- Singapore, chosen for its consistently successful science education and its historic links with the UK education system. We visited three secondary schools across Singapore and met with officials and master teachers at the Academy of Singapore Teachers and with science education academics at the National Institute of Education.
- The USA (Massachusetts). Massachusetts is the highest-performing US state in PISA. We visited three high schools in the Boston area and met officials in the Massachusetts Department of Education and the Boston Public School District.

Altogether, we visited a total of 19 schools across six countries. At each school we observed lessons, toured the science facilities and talked with students, science teachers, science department leaders and school leaders.

Figure 2: Our method and timetable

2015	
JANUARY – JULY	**Rapid Evidence Assessment:** desk research of the available research literature.
AUGUST – OCTOBER	**Preliminary survey** of 11 countries to identify expert witnesses and to get a consensus on the purposes of practical science.
2016	
NOVEMBER 2015– MAY 2016	**International visits** to six countries – Australia (Victoria), Finland, Germany, the Netherlands, Singapore, the USA (Massachusetts) – to see practical science in schools and to meet teachers, students and officials.
JUNE – SEPTEMBER	**First draft of benchmarks** and three consultation workshops.
DECEMBER	**Second draft of benchmarks,** used for school survey and costing exercise.
2017	
DECEMBER 2016 – JANUARY 2017	**School survey,** carried out by Pye Tait, to see how a 10% sample of schools in England measures up against the benchmarks.
JANUARY – MARCH	**Costing exercise,** carried out by PwC, to produce an analysis and commentary on the costs of implementing each benchmark.
MARCH – JUNE	**Analysis, writing and review.**

Desk research

Analysis, drafting and consultation

Fieldwork

2.3 FROM VISITS TO BENCHMARKS

We used these international visits to reflect on practice in UK schools, which we knew about from the literature and from numerous visits. From this analysis, we drafted 10 benchmarks to define the characteristics of good practical science (section 3).

Our methodology in this study is more like that of the Ofsted inspectorate, using professional judgements based on fieldwork and discussions with practitioners, than a series of controlled quantitative studies. Our expert witnesses in each country accompanied us on the school visits, helped us to evaluate and interpret what we saw and helped to validate our judgements.

Like any international comparative study, this method is open to confirmation bias – the temptation to cherry-pick findings to justify prior beliefs. We also appreciate that what we saw in one country would not necessarily translate readily to another, because much of educational success is culturally determined (see the box on Singapore). We had to use professional judgement, and consult experts, to decide which aspects of what we saw overseas could be replicated in the UK. To test our own judgements, we carried out three consultation workshops on the draft benchmarks with headteachers, teachers and education experts in the UK. Appendix 5 gives the names of the people we consulted.

SINGAPORE: ON TOP OF THE WORLD

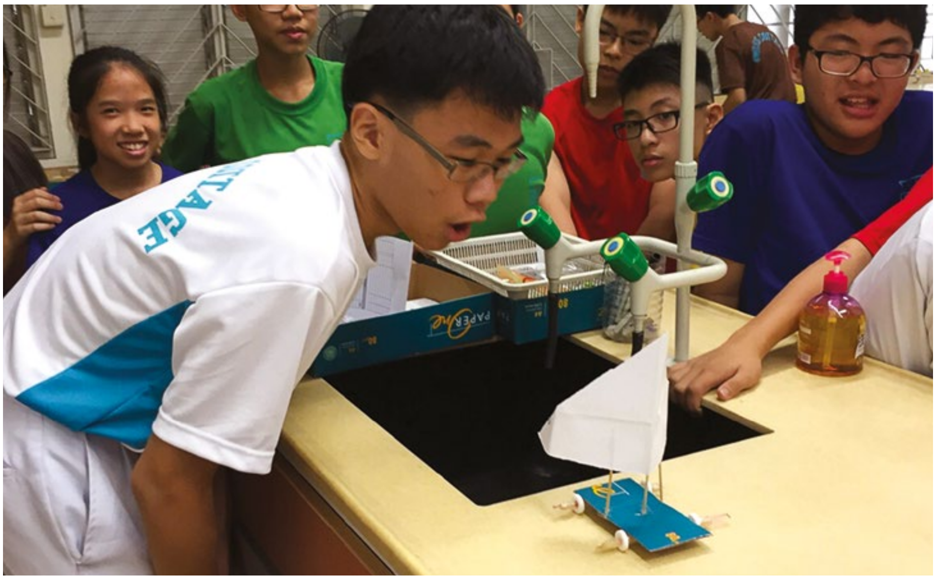
Singapore headed all three world subject rankings (mathematics, science and reading) in the 2015 PISA tests, following outstanding performances in the tests in 2012 and earlier years.

Education is held in high regard and families strive fiercely to get their children into the best primary schools, and so to the best secondary schools and the best universities. The system is unapologetically elitist and there is extensive provision for gifted students, with participation in international competitions like science Olympiads being highly prized.

Teaching is a prestigious profession with starting salaries higher than for doctors, and applications for training places can have a ratio of 40:1 in desirable subjects. In all the lessons we saw, students were co-operative and well behaved, and lessons were meticulously planned – all of which enabled effective practical science to take place in large groups of up to 40.

Some of the features of Singapore's success – such as the specialist training and systematic professional development of teachers – can be replicated elsewhere. But many features – particularly the deep respect for education and teachers – are embedded in the national culture and much harder to replicate.

> IN SINGAPORE, LESSONS WERE METICULOUSLY PLANNED, WHICH ENABLED EFFECTIVE PRACTICAL SCIENCE TO TAKE PLACE IN LARGE GROUPS



Left: Studying sustainable energy at Swiss Cottage School, Singapore

Above: Swiss Cottage School, Singapore

2.4 THE SCHOOL SURVEY

Following these consultations, we revised the 10 benchmarks. We commissioned Pye Tait Consulting to use them as the basis for a survey of about 10% of schools in England, to see how English schools measure up against the benchmarks. The results are summarised in section 4 and full details are in Appendix 4.

2.5 THE COSTING EXERCISE

We commissioned consultants PwC to provide an analysis and commentary on the costs of meeting each benchmark. The results are summarised in section 5 and the full report is available online at www.gatsby.org.uk/GoodPracticalScience

2.6 THE RECOMMENDATIONS

Having surveyed schools against the benchmarks, we drew up a set of recommendations for schools, government and other stakeholders. They are in section 6.

3

THE BENCHMARKS FOR GOOD PRACTICAL SCIENCE

IN THIS SECTION, WE DESCRIBE THE 10 BENCHMARKS FOR GOOD PRACTICAL SCIENCE, WHICH HAVE BEEN DERIVED FROM OUR OVERSEAS VISITS AND TESTED IN THREE CONSULTATIVE WORKSHOPS

These benchmarks are *input* measures: they define the things that schools and teachers should do to get good practical science. We have described each benchmark in a way that is measurable as far as possible, so that schools can see how they are doing against each. This was important when we carried out the school survey (section 4) and we hope it will also be useful for schools that read and use this report.

The benchmarks are written from the point of view of schools, because it is headteachers, governors and science leaders who make important decisions that affect practical science. However, we realise that policymakers and regulators create the context within which schools operate, through their control of funding, teacher supply, the national curriculum and the accountability framework. Our recommendations in section 6 are directed at policymakers as well as schools.

10 BENCHMARKS

Each benchmark statement includes a summary and a set of criteria showing what schools need to do to meet the benchmark. In the survey of English schools (section 4), we used these criteria to construct the survey questionnaire.

Figure 3: The 10 benchmarks for good practical science

1 PLANNED PRACTICAL SCIENCE	2 PURPOSEFUL PRACTICAL SCIENCE
3 EXPERT TEACHERS	4 FREQUENT AND VARIED PRACTICAL SCIENCE
5 LABORATORY FACILITIES AND EQUIPMENT	6 TECHNICAL SUPPORT
7 REAL EXPERIMENTS, VIRTUAL ENHANCEMENTS	8 INVESTIGATIVE PROJECTS
9 A BALANCED APPROACH TO RISK	10 ASSESSMENT FIT FOR PURPOSE

Right: Swiss Cottage School, Singapore

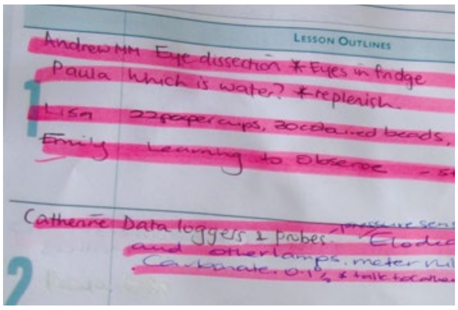
BENCHMARK 1: PLANNED PRACTICAL SCIENCE

Summary

Every school should have a written policy that explains why teachers use practical science, the outcomes they expect from it and how they achieve those outcomes. The process of producing the policy is as important as the policy itself.

Criteria

- The policy should be produced as a team effort by teachers and technicians across the science department.
- The policy should explain the differences in practical science between different age groups.
- The policy should say how special educational needs and disabilities (SEND) are accommodated.
- The policy should include any use of opportunities for practical science outside the school, in universities, employers, science centres etc.
- The policy should be annually reviewed against practice.
- There should be a member of the senior leader team who will act as a 'sponsor' for practical science among senior leaders.



Above: Planned practical science at Melbourne Girls' College, Australia

3.1 BENCHMARK 1: PLANNED PRACTICAL SCIENCE

Our visits to schools around the world show that practical science is most effective when teachers and students are clear about why they are doing it. This finding is backed up by the literature.[21]

We are saying that every school should have a written policy on practical science, **but the process of producing the policy is as important as the policy itself.** It should not be a bureaucratic exercise, but a process to encourage teachers and technicians to think collectively about why and how they approach practical science. It is likely to be led from within the science department, but a senior school leader should be involved. This is an opportunity to integrate science policy with whole-school policies on styles of teaching and learning. Practical science should feature in whole-school policies, making it clear that it is embedded in the school.

The detailed policy will vary from school to school, depending on the nature of the students and the overall ethos of the school. Because of this, we are stopping short of suggesting a model policy, though other organisations may wish to do so (see Recommendation 9).

We hope that schools will find our 10 benchmarks helpful in structuring the policy. The starting point for the policy should be the purposes of practical science (section 1.3). Thinking collectively about the purposes of practical science should lead naturally to consideration of frequency, approach and use of human and physical resources. Health and safety will of course be part of the policy, but the department should think about how it achieves a balanced approach to risk (Benchmark 9).

The policy should encourage teachers to innovate as well as using tried and tested experiments. It should refer to the way the school engages with universities, industries and science centres, and other outside organisations, in the context of practical science. If the school has a STEM Club,[22] it should be included in the policy.

The policy should describe how practical work in science is assessed.

The policy should be regularly reviewed against practice. This might be done annually, or triggered by the arrival of new members of staff or the introduction of significant curriculum changes.

The school survey (section 4) suggests that having a 'sponsor' member of the senior leader team with an overview of science can make a big difference to this and other benchmarks.

GERMANY: PLANNING TOGETHER

In Klosterschule, Hamburg, science teachers meet three times a year for major planning, and teams of teachers for each grade also meet once a week. It was acknowledged that this takes time away from teaching, and requires the support of parents, but it also results in confident teachers and a coherent, relevant and constantly improving curriculum. These days were not considered 'training' days – they were how the school was run and an integral part of science teachers' professional duties.

Following the most recent revision of national standards in the sciences, these planning meetings were used to agree the most appropriate practical activities for the school's science curriculum. Subsequent meetings were used to evaluate the success of those practicals and adapt them if necessary. The discussions also helped identify teachers who needed additional support from colleagues more confident in practical science.

BENCHMARK 2: PURPOSEFUL PRACTICAL SCIENCE

Summary

Teachers should know the purpose of any practical science activity, and it should be planned and executed so it is effective and integrated with other science learning.

Criteria

- Teachers should have a clear purpose for every practical activity and know how it relates to the rest of what they are teaching.
- Teachers should plan to their satisfaction how to introduce each practical and how to follow it up.
- Teachers should take account of students' special educational needs and disabilities (SEND) in their planning, so all students can participate equally.

3.2 BENCHMARK 2: PURPOSEFUL PRACTICAL SCIENCE

This benchmark is about how the thinking in Benchmark 1 (*Planned practical science*) is enacted by individual teachers.

PISA 2015[23] concludes that practical work in science must be 'meaningful'. In the best science lessons we saw, students knew what they were doing, and why. This is not to say that practical instructions always have to be spelled out in detail: teachers told us of the value of allowing students some flexibility when exploring an idea. We heard frequent warnings about conducting practical activities in a 'cookbook recipe style'. Wellcome's Science Education Tracker[24] warns that over a fifth of the students they interviewed in England often, "just followed instructions for practical work without understanding its purpose". In Finland we were struck by the sparse nature of many practical worksheets: students were given skeleton instructions and expected to work out the detail for themselves, but they knew why they were doing it.

Each practical science activity should fulfil a learning purpose and all students should be actively engaged and intellectually involved. Teachers need to plan for what students will be thinking as well as what they will be doing. Practical science activities need to be intellectually challenging: because they involve concrete objects, practical activities can be made more challenging than if the same ideas were presented in the abstract.

'Sense making' (following up experiments with discussion and reflection) is critical. Practical activities should be followed up by discussing the outcomes with the class, individually or collectively, if possible during the same lesson in which the activity is done. The beauty of practical science is its impact on the memory, but even that soon fades after a day or two, even more so after a week.

It isn't possible or necessary to meet all the five purposes of practical science (section 1.2) within a single practical activity, but teachers should reflect on which purpose(s) they are aiming for. Teachers shouldn't be over-ambitious in the purpose of an activity: just one purpose may be enough.

Practical science classes should be well organised so that students clearly understand what they are expected to do – while leaving flexibility to respond to unexpected outcomes from experiments. Teachers should try out any practical activity before they use it with a class for the first time; this is essential for risk-assessing an activity. Technicians are a critical support in the planning of practical science, but their trialling of an experiment should not be a substitute for teachers having the time and space to trial experiments for themselves.

We have seen the value of school-led curriculum design in other countries. In Germany, we saw that teachers have the freedom, and an appetite, to innovate by adding new experiments into their teaching.

THE USA: USING PRACTICAL WORK TO CREATE A SHARED EXPERIENCE FOR EVERY STUDENT

Chelsea High School is the only public High School in Chelsea, a city near Boston. It has a very high population of recently arrived migrants, with often more than 100 students joining the school through the year, many of whom do not speak any English. The large majority of students have Spanish as their home language.

The school has created a Basic Science course as part of their English Language Programme. We saw a lesson in which an experiment to measure the rate of cooling of hot water was used to create a common experience for the students. Students were able to learn about the scientific process while building their language skills as they sought out vocabulary to describe the experiment. The highly skilled bilingual teacher switched to Spanish when he perceived students were struggling to understand, then back to English. In this way, in a single science lesson students learned science, data handling and English.

It was clear to see the power of a concrete experiment to aid learning of an abstract concept. We later saw students in their senior year in the top Advanced Placement Physics class who had begun their science learning in these very same Basic Science Classes.

This curriculum wouldn't be appropriate for every student or every school, but the autonomy given to teachers in this school had led to a targeted and very effective course.

In England, teachers operate within a rigid curriculum specification, but they should still be encouraged to modify and innovate whenever they can. The great thing about experiments is that they give different results every time, but even so they can become stale when used for many years. Innovation of the kind we saw in Germany brings freshness to teaching.

BENCHMARK 3:
EXPERT TEACHERS

Summary

Teachers should have subject-specialist training (both initial and continuing) in the subject (biology, chemistry, physics etc.) and age range they teach, so they can carry out practical science with confidence and knowledge of the underlying principles.

Criteria

- At post-16 level, teachers should have a post-A level science qualification[25] related to the science subject they teach (biology, chemistry, physics), together with relevant pedagogical training.
- At pre-16 level, if teachers do not have a post-A level science qualification related to the subject they teach, they should have had sufficient additional training to give them the confidence, subject knowledge and skills to conduct effective practical work at that level.
- School science departments should review their teacher expertise annually, and ensure that individual needs for continuing professional development, including time for professional reflection, are being met. This should include specific training in practical science.

> SCIENCE TEACHERS IN GERMANY DO PRACTICAL WORK BECAUSE OF THEIR OWN SCIENCE EXPERTISE, AS WELL AS THEIR INHERENT BELIEF THAT SCIENCE IS PRACTICAL

GERMANY: TEACHERS AS SCIENCE EXPERTS

Researchers at the Leibniz Institute for Science and Mathematics Education (IPN) told us that science teachers in Germany do practical work because of their own science expertise, as well as their inherent belief that science is practical.

Teacher training involves studying to Masters level in two sciences as well as in pedagogy and educational theory, and this equips German teachers with a solid theoretical foundation to their teaching. Teacher education courses at university typically include laboratory classes and seminars covering skills in planning and performing experiments using school-level equipment. We observed a high degree of practical confidence and competence, with teachers devising new practicals and building sophisticated equipment.

3.3 BENCHMARK 3: EXPERT TEACHERS

Subject-specific qualifications are valuable across all aspects of science teaching, and particularly for teaching practical science. Teachers with subject-specific qualifications are likely to be more experienced and confident in working with the materials and equipment involved in their subject, to do so safely and to be able to explain the underlying theory.

In several of the countries we visited, we found that specialist science departments in universities played an active part in pedagogical training, and teachers told us of the confidence this gave them. Pedagogical training for science teachers should include aspects that are specific to practical science, such as health and safety, use of digital technologies, working with technicians, and providing for special educational needs and disabilities (SEND) in practical science.

Right: Klaus-Groth-Schule, Germany

Above: The Academy of Singapore Teachers, Singapore

Schools should place a high priority on recruiting teachers with subject-specific qualifications, but we realise that for many schools this is easier said than done. In many of the countries we visited, the subject expertise came from the initial training, but additional in-service training can have the same effect. Given the realities of teacher shortages in England, additional training may often be the only available route to scarce subject expertise. Additional training can bring teachers up to an acceptable level of subject-specific expertise, but it needs to be of high quality and where possible recognised by a body such as the Institute of Physics or the Royal Society of Chemistry.

Where schools do not have subject specialists to meet this benchmark, the school should plan to grow their teachers' collective subject expertise over time, through recruitment and additional training and through making the optimum use of those subject specialists they do have (Recommendation 7).

Subject expertise needs to be maintained throughout teachers' careers, so *continuing* professional development (CPD) is essential. The UK is fortunate in having high-quality CPD for science teachers available at low cost, or no cost, such as that provided through the Science Learning Partnerships,[26] the National STEM Learning Centre and ENTHUSE bursaries.[27]

CPD does not have to be external to the school: professional exchange is a highly effective form of CPD and should be embedded in everything science teachers do. Schools should encourage colleagues to visit one another's practical lessons to reflect and learn from them. In many countries we visited – and in an increasing number of schools in the UK – such professional interchange is the norm, and it is a powerful way to develop professional expertise. Newly and recently qualified teachers, in particular, need time to try out experiments before using them with a class.

We have to accept that cover teachers may lack the expertise benchmarked here, so they should not normally be expected to supervise practical lessons.

SINGAPORE: CAREER-LONG PROFESSIONAL DEVELOPMENT

Professional development is highly structured and valued in Singapore and a newly trained teacher is seen as someone at the beginning of their career-long journey. The Academy of Singapore Teachers (AST), part of the Ministry of Education, organises and coordinates professional development programmes. These include compulsory professional development (relating to statutory changes in curriculum and assessment), networking meetings and conferences, and a programme of courses – most of which run over several days – designed with input from practicing teachers.

There are three clearly defined professional pathways: Teaching (which leads to becoming a Master Teacher), Leadership (leading to school Principal and ultimately to Director at the Ministry of Education) and Specialist (specialising in a specific subject area). Teachers choose which track they intend to follow but are free to move between them.

While the highly centralised Singapore system would not be appropriate for the UK, we could use some of the value, prestige and structure given to professional development. This is something that England's new Chartered College of Teaching can take a lead on (Recommendation 3).

> GIVEN THE REALITIES OF TEACHER SHORTAGES IN ENGLAND, ADDITIONAL TRAINING MAY OFTEN BE THE ONLY AVAILABLE ROUTE TO SCARCE SUBJECT EXPERTISE

BENCHMARK 4: FREQUENT AND VARIED PRACTICAL SCIENCE

Summary

Students should experience a practical activity in at least half of their science lessons. These activities can be short or long, but should be varied in type.

Criteria

- On average, across the year and across all the sciences, at least half of lessons should involve direct practical activities, whether hands-on or teacher demonstration.
- Practical activities can be short or long. There should be enough long science lessons (of at least 50 minutes) in the timetable to give teachers flexibility about when they do experiments.
- Practical activities should be varied and balanced in type (see section 1.6).

> FREQUENT, SHORT PRACTICALS CAN HAVE MORE IMPACT THAN INFREQUENT, LONG ONES

3.4 BENCHMARK 4: FREQUENT AND VARIED PRACTICAL SCIENCE

Practical activities do not have to be long. Some of the best examples we saw were short, memorable experiments followed by lots of discussion. Frequent, short practicals can have more impact than infrequent, long ones. In Finland, a teacher told us: "I can't imagine a lesson in which I don't do some practical work."

The most effective science teaching we saw featured practical activities in at least half of all lessons. Our judgment of 'at least half' comes from talking to teachers and technicians and asking them to estimate how often a lesson featured some practical activities, on average across all ages and subjects. However, it did vary according to the age of the students, the time of year, the science subject and the topic being taught. We observed from the schools we visited that practical work is less frequent with older students, and less frequent in biology than in physics and chemistry.

GERMANY: SIMPLE EXPERIMENTS

In two German schools, we saw the value of simple experiments.

In Kieler Gelehrtenschule we saw a chemistry class of 13 year olds identifying what turned out to be a coffee bean, by heating it. This intriguing experiment involved close observation, safe heating, accurate drawing and much follow-up discussion.

In Klaus-Groth-Schule we saw a demonstration with a chemistry class of 11 year olds. The teacher dropped an effervescent vitamin C tablet into a beaker of water and then floated a small tealight candle on the water. After a while the candle flame was extinguished. Students were then given a set of kit from which to build a 'fire extinguisher'. Students were very engaged but the teacher kept a lid on any unruly excitement by communicating slowly and quietly, and giving them plenty of thinking time when he asked a question.

'Half' does not mean that half of the total time spent on science should be practical work. It means that half of the lessons should feature a practical activity. These activities can be short or long. For teachers to have the freedom to do frequent practical activity, they need to be timetabled in a laboratory as much as possible, preferably for all lessons (Benchmark 5).

Frequency alone is not enough: practical activities need to be planned and purposeful as well as frequent, and quality is critically dependent on the skill and confidence of the teacher (Benchmarks 1, 2 and 3).

There should be a balance and range of *types* of practical work (see section 1.6 *Types of practical science*). This will vary across the sciences. In biology in particular, practicals may stretch over a long period, because living things often change slowly.

Left: Damstede School, the Netherlands

BENCHMARK 5: LABORATORY FACILITIES AND EQUIPMENT

Summary

Schools should have enough laboratories to make it possible for every teacher to do frequent practical science safely. Each laboratory should have sufficient equipment for students to work in small groups.

Criteria

- There should be enough laboratories so that the availability of labs is never a barrier to carrying out practical activities in the science subjects taught.
- Laboratories should be large enough to safely accommodate the size of classes that will occupy them.
- The spaces should be flexible enough to allow students to work individually, in pairs and in small groups.
- There should be sufficient equipment to make it possible for teachers to do standard practical activities expected in their specialist subject at that level.
- There should be ready access to the technology required to enable collection and analysis of digital data.
- Laboratories should be accessible to students with any special educational needs and disabilities (SEND) encountered in the school.
- The school should have laboratory facilities such that students can carry out extended practical science investigations (see Benchmark 8).
- There should be a preparation space or spaces with well-organised, safe storage with easy access to laboratories.
- There should be an accessible outdoor space where practical activities can take place.

3.5 BENCHMARK 5: LABORATORY FACILITIES AND EQUIPMENT

Good practical science is difficult without good laboratory facilities. PISA 2015 found a strong correlation between well-equipped labs and performance in the PISA tests.

Schools in England generally measure up well against the best international standards for laboratories and equipment. Benchmark 5 sets out expectations based on what we have seen overseas, but we have also considered what we know about schools in England and the guidance given to schools by government and professional bodies on building design.[28]

When schools are being built from new, or refurbished, it is important that laboratories are designed to meet the expectations in this benchmark. We urge school leaders and architects to take heed of them, and to use the detailed advice available from CLEAPSS,[29] the Department for Education (DFE) and the Association for Science Education.[30] Our survey of English schools (section 4) suggests that the expert views of science teachers and technicians may not always be considered when designing new labs.

What is appropriate will depend on the age of the students. In particular, post-16 (especially A level) classes are generally smaller and can be accommodated in smaller labs, but they need more specialist labs and equipment.

The availability of labs should not be a barrier to carrying out practical activities. In some of the schools we visited, each teacher had their own laboratory, and in many schools it was the norm for every lesson to be timetabled in a laboratory (as opposed to a classroom). These arrangements make it easier for teachers to do practical activities whenever they wish, giving them more flexibility in planning. In practice, even in well-equipped England not every lesson can be timetabled in a laboratory, but schools should try to optimise the arrangements to give teachers maximum flexibility.

Left: Science Centre, Singapore

AUSTRALIA: THE NETWORK OF SCIENCE CENTRES

The Science Centres were established by the Victorian Government in 2012, following an initiative to provide opportunities for students to experience cutting edge scientific research. There are six centres spread across Victoria, each specialising in a different aspect of science or technology. We visited two centres in Melbourne: Quantum Victoria, specialising in the physical sciences, and the Gene Technology Access Centre (GTAC).

The Centres have performance criteria requiring them to engage with all schools in Victoria, with particular emphasis on inaccessible rural schools and on socioeconomic deprivation. They have an interesting model for reaching remote rural schools, involving a combination of ICT, video links and outreach visits. GTAC runs an innovative programme that trains and pays PhD students to run practical sessions with students.

The Science Centres are very well equipped with laboratories and equipment, and there is a strong emphasis on practical activity. At GTAC, we were told there is a lot of interest in using the centre's facilities for assessed investigations. The Centres also provide CPD for the teachers accompanying their classes.

Laboratories should be large enough to safely accommodate the classes that will occupy them. Except in Singapore, we rarely saw classes larger than 25. In general, smaller classes make for more effective practical activities, but we are stopping short of suggesting a maximum class size, such as the upper limit of 20 that applies in Scotland.[31] We recognise that in England this is impossible at present, so the benchmark is in terms of safely accommodating existing class sizes. Each school will know its own circumstances, so the policy should make it clear how the available laboratories are suited for the different age, size and ability of classes found in the school.

The spaces should be flexible enough to allow students to work individually, in pairs and in small groups. There are benefits from working in groups, in terms of social and co-operative skills, as we saw in Finland. However, there are other benefits in students being able to carry out activities individually from time to time so that individual students can develop particular skills. So there should be enough core equipment to make it possible for students to work individually when the teacher sees fit.

There should be a preparation space or spaces with well-organised, safe storage. In some schools this is a single, all-purpose space, in others there are separate spaces for the three main sciences. The advantage of an all-purpose space is that technicians and teachers can communicate and co-operate better, but it is important that the space has the specialist equipment needed for the sciences being taught in the school.

Many schools, overseas and in England, use other organisations (universities, local businesses, science centres, other schools) to access equipment that they don't have themselves. This can have other, wider benefits in terms of access to expertise and role models.

Access to a greenhouse, a pond and further ecological space in the school grounds help schools to deliver a rich biology curriculum to both pre- and post-16 students.

Wherever possible, digital devices should be accessible for students to use directly in the laboratory rather than going to a separate computer suite. Our survey of schools in England suggests that this is only the case in just over a quarter of schools.

Below: The Gene Technology Access Centre, Australia

SCIENCE FACILITIES IN THE UK

In the 1960s and 1970s, the Nuffield Foundation supported the development of new science curricula, which placed strong emphasis on practical scientific discovery. These influential developments coincided with an active period of school building in the UK, and it became the norm that newly built schools would include high quality laboratories and equipment.

From that time on, UK secondary schools have normally been well provided with lab facilities and technician support. As science has moved from an elite study to a universal entitlement, it has become expected for UK schools to be well provided, by international standards, with science facilities.

BENCHMARK 6: TECHNICAL SUPPORT

Summary

Science departments should have enough technical or technician support to enable teachers to carry out frequent and effective practical science.

Criteria

- For an average-size school, there should be specialist technical expertise to support practical work in each of biology, chemistry and physics.
- Technicians should be given regular opportunities to have professional development.

Above: Klosterschule, Germany

“TECHNICIANS UNDERPIN MOST OF OUR 10 BENCHMARKS, AND REDUCING TECHNICIAN SUPPORT PUTS ADDITIONAL DEMANDS ON TEACHERS WHO ARE ALREADY HARD TO RECRUIT AND RETAIN”

3.6 BENCHMARK 6: TECHNICAL SUPPORT

Technicians are a vital part of the science department team. Not only do they curate equipment and prepare experiments on a day-to-day basis, they also work with teachers to develop new practical activities, they are often expert in health and safety, and they are responsible for the purchasing of equipment and consumables. They are important for the morale of the science team. Indeed, technicians underpin most of our 10 benchmarks, and reducing technician support puts additional demands on teachers who are already hard to recruit and retain.

The technician support system in the UK is long established, and a move to systems like the USA or Finland would be a radical step that would incur major initial and ongoing costs. Government and headteachers need to be realistic about the result of reducing the technician team. It is likely to lead to risks to health and safety, a reduction in the quantity and quality of practical science, and incur additional costs.

We are clear that there should be technical support for each of biology, chemistry and physics – though this does not necessarily mean a different technician for each subject. However, even in the countries that employ school science technicians, the number varies and is not directly proportional to the size of the school. We are therefore not making a specific recommendation about the number of technicians needed for a school of a particular size.

SCIENCE TECHNICIANS IN THE UK

Science education in the UK has some of the best technician support we have seen anywhere, and this should be conserved and used to its full potential.

In our visits, we saw three countries (the Netherlands, Singapore and Australia) that employ school laboratory technicians, as in the UK, and three (the USA, Germany and Finland) that do not. Schools in countries that have no technicians have other ways of providing technical support. In the USA, we saw a centralised ‘kit in a box’ scheme run by the School District board, and we also saw schools where each lab has its own ensuite mini-prep room for the teacher to use without leaving their class. In Finland we learned that teachers are paid extra to cover the time needed to prepare experiments and order and maintain equipment. Such measures as these may begin to compensate for the absence of technicians, but they have significant costs.

Above: Science Technician, Haringey Sixth Form College, UK

THE NETHERLANDS: MAKING GOOD USE OF TECHNICIANS

Dutch schools are well provided with science technicians, who usually work part-time. The schools we visited had at least one technician for each separate science. The technicians we met were generally confident and proud of their role in the school, and are appreciated and relied on by teachers.

Technicians play an active role in helping the teacher and students in lessons. They are particularly valued as a support for the final year project, the *profielwerkstuk* (section 3.8) where they provide direct technical advice to students. Technicians may also help with the assessment of students' practical assignments for external qualifications.

Our survey of English schools (section 4) emphasises that experienced technicians are enablers for other benchmarks. Technicians free up teachers' time for lesson planning and preparation, and they support and help train less experienced teachers. They optimise the use of available labs and equipment. But our survey also shows the challenge of finding technicians with the right experience, given the low salaries that are often paid.

For technicians to provide the best quality support in a school, their professional status should be recognised and they need to be given regular opportunities for continuing professional development. Technicians should also have opportunities to achieve professional recognition such as Registered Science Technician (RSciTech).[32]

Schools may find that promoting at least one technician to a senior position enables the team to be more effective.

One downside of relying on science technicians is that it encourages an attitude of 'leaving it to the technician' to clean up and clear away. We were impressed in Finland, Germany and the USA (where there are no technicians) with the way students learned to clear up their apparatus at the end of the lesson, as a matter of routine. Teaching students how to safely dispose of chemicals and store equipment gives them a valuable skill even in a system supported by technicians.

The contribution of technicians can be enhanced by giving them opportunities to interact with students, both in lessons and as part of extra-curricular activities, as we saw in the Netherlands.

> “AS THE VIRTUAL WORLD BECOMES MORE ACCESSIBLE AND REALISTIC, AUTHENTIC EXPERIENCE IN THE REAL WORLD BECOMES MORE, RATHER THAN LESS, IMPORTANT”

BENCHMARK 7:
REAL EXPERIMENTS, VIRTUAL ENHANCEMENTS

Summary

Teachers should use digital technologies to support and enhance practical experience, but not to replace it.

Criteria

- Virtual environments and simulated experiments have a positive role to play in science education but should not be used to replace a good quality, hands-on practical.
- Digital technologies are rapidly evolving and teachers should have access to evidence about what works, and training in their use, before implementing them in their science lessons.

3.7 BENCHMARK 7: REAL EXPERIMENTS, VIRTUAL ENHANCEMENTS

There is an important difference between real, hands-on experiments and virtual simulations of experiments, created by computers. Our visits suggest that even in the most advanced technological nations, digital technology is *not* replacing hands-on experiences. Perhaps, as the virtual world becomes more accessible and realistic, authentic experience in the real world becomes more, rather than less, important. In the best science teaching we have seen, digital technology has been used as an adjunct to, rather than a replacement for, real experiences.

Of course, there is a place for digital technology in science teaching. Modern laboratory science in universities and industry is heavily computerised, and students need to get a feel for this. Simulated experiments can enable students to have an experience of practical science that might be too complex or too dangerous in the school laboratory. Virtual environments can give access to data from remote places such as robotic telescopes and inaccessible environments.

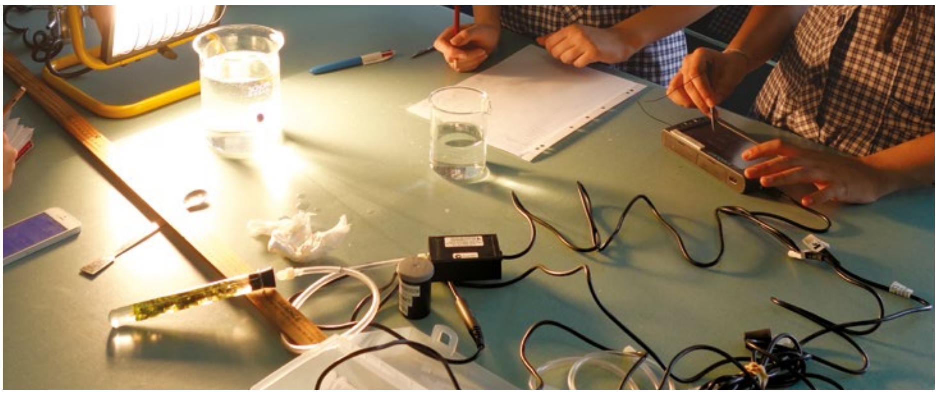
Using data loggers and sensors, interfaced with computers, enables students to collect data faster and more precisely, over extended periods. But, however sophisticated the data handling technology may be, it can never aid understanding unless students themselves engage intellectually with the data.

We saw no evidence that science teachers believe the benefits of virtual experiences outweigh those of hands-on practical science. Instead we saw science teachers preferring to use environments and experiments over which they had control and which met their students' needs.

Evidence is limited for 'what works' in using digital technology to support practical science. Our overseas visits gave us limited insights, because digital technology was often most notable for its absence. A review from the USA by Brinson[33] looked at computers versus traditional (hands-on) laboratory activities and found that the advantage of the virtual approach was greatest for knowledge outcomes measured by tests, and least for attitudinal outcomes assessed by quantitative methods. Burkett and Smith[34] argue that as yet there is no conclusive evidence that virtual simulations are effective, and recommend that they are used to supplement rather than replace hands-on labs. This matches our own experience: everything we know about hands-on tells us that virtual experiments are no substitute for the real thing, and a blended approach seems the most fruitful.

Teachers' professional development should include training in the effective use of digital technology to support practical science. Too often technology, such as data loggers, is purchased but left unused. Training on how to make use of the technology to support practical science will prevent resources being wasted.

Below: Using digital technology at Melbourne Girls' College, Australia



THE USA: USE YOUR OWN PHONE

Students' own devices, especially smartphones, can be powerful digital devices for collecting experimental data. We recognise that there are downsides to any policy of 'Bring your own device', and schools will need to balance these against the upsides, which in the case of practical science are likely to grow.

In Massachusetts, we saw fluent use of technology within the classroom, particularly in physics, including the use of tablets, data loggers and students' own smartphones. We saw students using their phone to film one another throwing balls, and then returning to class to track trajectories and plot graphs. Students used the associated software packages with ease. Technology was not shoehorned into the activities but used to enhance and support learning.

BENCHMARK 8: INVESTIGATIVE PROJECTS

Summary

Students should have opportunities to do open-ended and extended investigative projects.

Criteria

- There should be opportunities for students to do open-ended extended investigative projects in science.
- The school should have laboratory facilities such that all students who want to can carry out extended practical science, particularly among post-16 year olds.

3.8 BENCHMARK 8: INVESTIGATIVE PROJECTS

By 'open-ended' we mean an investigation for which there is no pre-determined outcome, and by 'extended' we mean spread across one or more weeks (see section 1.6 *Types of Practical Science*).

Even before our overseas visits, we already knew the impact that extended investigative practical projects can have. Wellcome's report *Young Researchers*[35] shows how these projects can give students experience of what it is like to do 'real' scientific research. At the same time, they develop resilience and skills in planning, problem solving and enterprise which are valued by employers.

Giving students the opportunity to conduct extended, in-depth experimental work on a topic that interests them can be a pinnacle of their school experience. It can change attitudes to science for a lifetime. We know from research[36] that open-ended, extended investigative projects are linked to improved attainment as well as motivation to continue with science. They can also have a particular impact on students from socially disadvantaged backgrounds – though the Science Education Tracker[37] shows that, at present, students from deprived backgrounds have fewer opportunities to do projects.

Our overseas visits reinforced this view, and gave us insights into how extended projects can work in practice. We were especially impressed by the *profielwerkstuk* projects that are carried out by all pre-university students in the Netherlands (see box) – a model that we believe could be adopted in England (see Recommendation 6).

THE NETHERLANDS: THE *PROFIELWERKSTUK*

The Dutch *profielwerkstuk* is an 80-hour independent research project. It is carried out by all students preparing for university entrance. Students follow one of four profiles (tracks) to university and their *profielwerkstuk* must relate to their chosen profile. Each year around 20,000 students do STEM projects, around 80% of which are practical. The work is spread over several months between the end of the penultimate year and January of the final year, and in some schools the timetable is suspended for a week while students work on their projects. They often work in small groups of two or three.

In a typical school, there might be about 20 projects involving practical science, hence the need in the schools we visited to have dedicated space for students' project work. During the project period, a lot of the laboratory technicians' time is spent supporting students' projects. We saw some impressive projects in all three of the Dutch schools we visited, and the students we spoke to took their projects very seriously.

Projects can be done with support from industry or a university. Some universities have telephone 'helpdesks' dedicated to supporting students' *profielwerkstuken*.

Examples we saw in our visits:

– At Damstede School, Amsterdam, two students using a data-logging kit to analyse harmonics in the human voice to see if there is a detectable difference between ethnic groups.

– Also at Damstede School, a student devising new experimental work for the school to use with younger students, linked to the germination of seeds.

– At Amsterdam Lyceum, a student investigating the psychological state of kidney patients preparing to undergo dialysis.

Left: Students at Damstede School in the Netherlands doing a *profielwerkstuk* project on the human voice

Above: Student researchers at Raffles Institution, Singapore

> STUDENTS BENEFIT FROM DOING PROJECTS FROM AN EARLY AGE AND CONTINUOUS EXPOSURE TO THIS KIND OF ACTIVITY HELPS THEM DEVELOP THEIR PROJECT SKILLS

UK: STEM CLUBS

STEM Clubs give students opportunities to do science, technology, engineering and mathematics activities outside the formal curriculum. In 2016 over 85% of secondary schools in the UK had at least one STEM Club. They can be for all ages, although the majority are for 11–14 year olds.

STEM Clubs take many forms. Most are created and led by teachers and technicians, and can take place after school or in lunchtime. Activities can be simple experiments or more ambitious projects such as at the Thomas Hardye School in South West England, where the STEM Club has worked on a project which genetically profiles ticks collected by volunteers to discover whether they contain the bacteria that cause Lyme Disease.

Advice and support on setting up STEM Clubs is available from the National STEM Learning Centre. www.stem.org.uk/stem-clubs

SINGAPORE: RESEARCHERS IN RESIDENCE

The research and project spaces we saw in Raffles Institution, Singapore, were the best we have seen anywhere. Several project spaces are available for use across the school. They are staffed by full-time technicians and 'researchers in residence'. Students are encouraged to use the spaces independently to initiate projects, to have discussions with the researchers and to read academic literature.

Most students carry out their projects at the end of the academic year and into the summer holidays. The aim of the lab and project spaces is to encourage students with special interest and ability in science and to create opportunities for excellence, often in national or international competitions and even resulting in scientific publications. There is a month-long teacher placement scheme in which school staff can work on a project with a researcher in residence to develop their own research skills.

The project labs at Raffles Institution contained advanced facilities including powerful computers, 3D printers, clean rooms, spectrometers and advanced centrifuges. Funding for this activity is provided by the Ministry of Education, and by industry and alumni.

Students benefit from doing projects from an early age and continuous exposure to this kind of activity helps them develop their project skills. We believe there are particularly rich opportunities for open-ended investigative projects in A level and other post-16 study.

We realise that supporting projects can be a significant burden on teachers and technicians as well as students and so our benchmark relates only to providing *opportunities* for projects rather than saying they should be compulsory. Our survey of English schools (section 4) shows that, for now at least, this is an aspirational benchmark, with only 15% of respondents saying that all of their students have the opportunity to do an extended practical science project.

Even so, there are many ways that projects can be fitted in. Within the curriculum in England, there may be opportunities during Key Stage 3, where the curriculum is less prescribed, and with Extended Project Qualifications (EPQs) for post-16 students. Outside the curriculum, there are opportunities using STEM Clubs, Royal Society Partnership Grants[38] and through nationally validated schemes such as CREST[39] and Nuffield Research Placements,[40] which can validate project work both inside and outside lesson time.

Investigative projects can be greatly enhanced by the involvement of researchers from outside the school, particularly from universities and industry. The Institute for Research in Schools[41] exists to support and encourage school-based research, especially in conjunction with universities.

BENCHMARK 9: A BALANCED APPROACH TO RISK

Summary

Students' experience of practical science should not be restricted by unnecessary risk aversion.

Criteria

- Responsibility for safety is shared between the school or local authority as employer, the teacher and the technician. This should be clearly understood by all members of science staff.
- The school should ensure that teachers and technicians have access to authoritative and up-to-date guidance including model risk assessments.
- Teachers should assess the risks and benefits for every practical activity, and act accordingly.
- Teachers and technicians should adopt a balanced and proportionate approach to managing risks, and be supported by senior management in doing so.

3.9 BENCHMARK 9: A BALANCED APPROACH TO RISK

In our visits overseas we saw a range of approaches to the risks of practical science. The best examples were where safety precautions were proportionate to risk and enabled varied practical science to take place. We have also seen examples where risk aversion has led teachers to remove some of the most engaging elements of practical science.

Practical science must obey the highest standards of safety and teachers should ensure that they consider how to best manage the risks for every practical activity, as required by their employer. The ultimate responsibility to carry out the risk assessment rests with the employer.[42] In schools and colleges in the UK, education employers meet their responsibilities by providing employees with model risk assessments, which the employee must then adapt to their own circumstances. So, the process of risk assessment needs to be a seen as a partnership between the employer, the provider of specialist guidance and the employee.

Teaching students to assess and mitigate risk as a routine part of practical science is a valuable part of their education and will serve them well in their future lives and employment. Taking responsibility for dealing with risk is an essential part of growing up. As Judith Hackitt said when Chair of the Health and Safety Executive:[43] "Overprotective parents and risk-averse teachers who do not enable children to learn about how to handle risk will lead to young adults who are poorly equipped to deal with the realities of the world around them, unable to discern real risk from trivia, not knowing who they can trust or believe. They will be a liability in any workplace if they do not have those basic skills to exercise judgment and take responsibility for themselves."

Teachers and technicians should adopt a balanced and proportionate approach to managing risk, and be supported by senior management in doing so. School leaders have an important role to play in setting the right tone for a balanced approach to risk. The tone set at the top of the school will send a signal that soon reaches school laboratories. Teachers with good subject expertise are likely to be more confident in doing practical science and more likely to take a balanced approach to risk. This reinforces the importance of expert teachers (Benchmark 3).

There are many myths about what is safe in school science and what is not, and expert advice from a specialist organisation such as CLEAPSS[44] and SSERC[45] can save schools from unnecessary over-reaction to safety concerns. CLEAPSS and SSERC provide schools with expert advice on laboratory safety and provide balanced advice and model risk assessments for standard school experiments. We recommend that in England all schools should belong to CLEAPSS, either individually or through their local authority or academy trust (Recommendation 10).

CLEAPSS covers Wales and Northern Ireland as well as England. In Scotland, a similar role is performed by SSERC.

Below: Kieler Gelehrtenschule, Germany

BENCHMARK 10: ASSESSMENT FIT FOR PURPOSE

Summary

Assessment of students' work in science should include assessment of their practical knowledge, skills and behaviours. This applies to both formative and summative assessment.

Criteria

- Teachers should reflect on students' practical skills and knowledge when awarding a grade for science.
- Teachers should regularly use practical activities as an opportunity to formatively assess students' understanding of science.

FINLAND: TEACHER ASSESSMENT OF PRACTICAL SCIENCE

For the teachers we spoke to in Finland, practical work was a means to achieve a stronger engagement with scientific knowledge. The results would be evident in the choices students made to continue with science post-16, and in the results of their matriculation exam at 18.

At Nöykkiö School, a teacher of physics and chemistry designs simple summative tests for his courses, tweaking them each year to ensure variation between year groups. He told us he preferred not to assess directly through practical work because of the likelihood of unexpected incidents, but the tests he creates are based on the practicals the students have recently undertaken, giving him confidence that they can draw on the experience when sitting the test.

At Helsinki Normal Lyceum, one teacher of physics and chemistry gives all her Grade 9 students a written report assessing how 'active' they have been in their practical work, and how well they have participated in discussions around experiments. She encourages her students to grade themselves, and if their grade differs from the one she gave them she is open to negotiation.

3.10 BENCHMARK 10: ASSESSMENT FIT FOR PURPOSE

Our starting point is that practical skills are an important part of science learning. So these skills should be assessed along with all the other important elements of science learning. Assessment of practical skills and knowledge should be both formative, to shape learning, and summative, to assess the standard a student has reached. In the good practical science that we saw overseas, assessment was part of good teaching.

But summative assessment carries baggage with it. Teaching in England is remarkable for the powerful accountability system (Ofsted and published performance tables) within which it takes place – strikingly so when compared with the overseas countries we visited. The combination of accountability and a heavy emphasis on assessment for national qualifications means that the behaviour of teachers, and the attitudes of students, are strongly shaped by assessment requirements.

In the countries we visited, teachers generally had more control over both curricula and assessment, particularly for 14–16 year olds, than in England. We rarely heard either teachers or students suggest that external assessment requirements inhibited good teaching and learning. On the other hand, it is sometimes claimed that assessment has a negative impact on practical science in England.[46]

All our benchmarks for good practical science are about factors within the control of schools and teachers. We realise that external assessment – particularly at ages 16 and 18 in England – has a powerful effect in shaping the way teachers do their job. But external assessment models are largely beyond the influence of teachers. So Benchmark 10 is about assessments carried out by teachers *other than* for external qualifications like GCSE and A level. In Recommendation 5 we discuss what we think should happen to assessment of practical science in external qualifications.

Assessment of practical skills and knowledge should be valid – in other words it really should assess practical skills and not something else. In most of the cases we saw and heard of overseas, this means *direct* assessment by the teacher, by observing the student at work. Only in Singapore did we come across formal practical examinations.

We heard about examples of practical skills and knowledge being assessed *indirectly*, by means of written questions set in a practical context. We need reassurance that this is a valid means of assessing *practical* knowledge, especially in England where the assessment stakes are so high and teachers are so skilled at coaching students to perform in written questions. We believe that more research needs to be done on how practical skills can be validly assessed using indirect methods (Recommendation 5).

Our survey of English schools suggests that the arrangements for assessing practical science at A level and GCSE introduced from 2015 and 2016 may be having a wider influence on formative assessment of practical skills (see section 4.3).

4

HOW DO ENGLISH SCHOOLS MEASURE UP?

THE 10 BENCHMARKS GIVE THE INGREDIENTS FOR GOOD PRACTICAL SCIENCE BY WORLD STANDARDS. BUT HOW DO SCHOOLS IN ENGLAND MEASURE UP?

We wanted to know so we could see whether our benchmarks are realistic for England, how far schools have to travel and what recommendations we should make. To find out, we surveyed a 10% sample of secondary schools and colleges in England. We also commissioned a costing exercise to help us understand the realities, in terms of time and money, of implementing the benchmarks (section 5).

4.1 THE SCHOOL SURVEY

We asked Pye Tait Consulting to construct a survey based on the criteria in each benchmark. Invitations to take part in the survey were sent out to senior contacts and heads of science in schools and colleges in England, and the survey was conducted between 28th November 2016 and 26th January 2017.

Returns were provided by almost 400 schools, which is about 10% of schools in England. These data were used for the analysis. Appendix 4 online at **www.gatsby.org.uk/GoodPractialScience** has full details of the survey and its results.

Follow up in-depth interviews were conducted with 20 respondents, selected to give a cross-section of school types, sizes and regions. These qualitative interviews were revealing. Importantly, they confirmed that many of the benchmarks are essential ingredients of *all* science teaching – not just practical science.

The survey respondents were from all types of maintained schools across all regions of England. The large majority (77%) were heads of science.

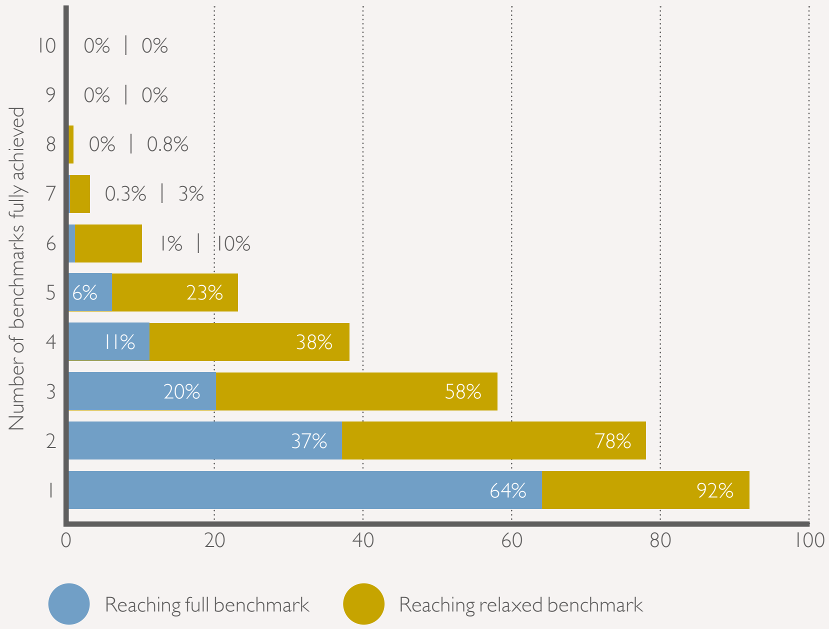


Figure 4: Percentage of schools reaching different numbers of benchmarks

> THE DETAILED ANALYSIS OF BENCHMARK CRITERIA SHOWS THAT MANY SCHOOLS ARE WELL ON THEIR WAY TO ACHIEVING THE FULL BENCHMARK, BUT ARE NOT QUITE THERE

4.2 SURVEY RESULTS: THE OVERALL PICTURE

Meeting all the criteria for all the benchmarks is very demanding, and the survey confirms that most schools are well short of achieving world-class practical science measured in this way (Figure 4). Just over a third (36%) reach no full benchmarks at all, and no school reaches more than seven full benchmarks. Meeting a benchmark requires meeting all the criteria within it, and the detailed analysis of benchmark criteria shows that many schools are well on their way to achieving the full benchmark, but are not quite there. Some benchmarks, for example, Benchmarks 4 and 5 are multi-faceted, with numerous criteria, and this makes them particularly hard to achieve in full.

The full analysis in Appendix 4 has the detailed breakdown of the survey results by school type, size and other characteristics (including rich analysis of correlations), and indicates the distance schools have to go to fully achieve all benchmarks.

Appendix 4 also shows the effect of 'relaxing' some of the benchmarks. 'Relaxing' the benchmark criteria means making some of them less demanding, while retaining the essence of the benchmark. For example, in Benchmark 1, instead of requiring *all* schools to have a written policy, the relaxed benchmark is met by schools with a written policy *or with plans in place to develop a written policy*. When relaxed benchmarks are used, only 8% of schools reach no benchmarks at all.

36%

The percentage of schools that reach no full benchmarks at all.

8%

The percentage of schools reaching no benchmarks when the benchmarks are relaxed.

4.3 SURVEY RESULTS: BENCHMARK BY BENCHMARK

Benchmark 1: Planned practical science

Nearly two-thirds of schools have discussions involving the whole science department about why and how they use practical science, but only 23% are capturing these discussions in a written policy and not all are reviewing it regularly. The qualitative interviews underlined how valuable it is to have a member of the senior leader team with an overview of practical science, which 40% of schools currently do. We see Benchmark 1 as an enabler for other benchmarks, and a quick win for schools wanting to make progress.

40%

The percentage of schools that have a member of the senior leader team with an overview of practical science.

BENCHMARK 1: PLANNED PRACTICAL SCIENCE Every school should have a written policy that explains why teachers use practical science, the outcomes they expect from it and how they achieve those outcomes. The value of having a written policy lies in the process of its production	% of schools
Schools that have a written policy	23%
Schools with a written policy where the head(s) of department, science teachers and technicians were all involved in its development	31%
Schools with a written policy that have discussions among the science department team, including all teachers and technicians, as and when required, of:	
– Why teachers use practical science, the outcomes they expect from it and how they achieve those outcomes	44%
– The different approaches to practical science in different age groups	42%
– How special educational needs and disabilities (SEND) are accommodated	59%
– Use of opportunities for practical science outside the school, in universities, industry, science centres etc	50%
All schools that have discussions among the science department team, including all teachers and technicians, as and when required, of:	
– Why teachers use practical science, the outcomes they expect from it and how they achieve those outcomes	61%
– The different approaches to practical science in different age groups	54%
– How special educational needs and disabilities (SEND) are accommodated	67%
– Use of opportunities for practical science outside the school, in universities, industry, science centres etc	58%
Schools with a written policy annually reviewing this against practice	67%
Schools with a member of the senior leader team with an overview of practical science	40%
Schools with a written policy that have a member of the senior leader team with an overview of practical science	10%

Below: St. Bonifatiuscollege, the Netherlands

Benchmark 2: Purposeful practical science

Under half of schools are fully achieving this benchmark, which is a cause for concern. There is a strong correlation between schools that score highly in this benchmark and schools where all teachers have time for professional reflection with colleagues (part of Benchmark 3).

However, the detailed analysis shows that the percentages rise substantially when the criteria are relaxed to include 'all or the vast majority of teachers' instead of 'all teachers'. For example, when this relaxation is applied to the criterion *Schools where all teachers should have a clear purpose for every practical activity and know how it relates to the rest of what they are teaching*, the percentage rises from 40% to 83%. It may be that in many science departments there are just a small number of teachers who, perhaps through inexperience, are not as purposeful as the benchmark requires.

22%

The percentage of schools where all science teachers have regular training specific to practical science.

Benchmark 3: Expert teachers

The survey, together with the qualitative interviews, confirms that the supply of specialist science teachers is a critical factor for English schools. More than a quarter (28%) of schools have at least one A level science teacher without a post-A level science qualification in the subject they teach. Many more (estimated at 69%) have at least one 11–16 science teacher who lacks this qualification, and in only 27% of schools have these teachers had sufficient additional training

We see professional development and reflection time as important ways of addressing specialist shortfalls, but fewer than half of schools are able to give all their teachers this time. Specialist teacher shortages fuel a vicious cycle: teachers in an understaffed science department need to teach more lessons, so they have less time to support non-specialist colleagues. We say more about teacher supply in Recommendation 2.

BENCHMARK 2: PURPOSEFUL PRACTICAL SCIENCE Teachers should know the purpose of any practical science activity, and it should be planned and executed so it is effective and integrated with other science learning	% of schools
Schools where all teachers have a clear purpose for every practical activity and know how it relates to the rest of what they are teaching	40%
Schools where all teachers plan, to their satisfaction, how to introduce each practical science activity to students before it is started	36%
Schools where all teachers plan, to their satisfaction, how to follow up each practical science activity with students	32%
Schools where all teachers take account of students' special educational needs and disabilities (SEND) in their planning, so all students can participate equally	36%

WE SEE PROFESSIONAL DEVELOPMENT AND REFLECTION TIME AS IMPORTANT WAYS OF ADDRESSING SPECIALIST SHORTFALLS

BENCHMARK 3: EXPERT TEACHERS Teachers should have had subject specialist training (both initial and continuing) in the subject (biology, chemistry, physics etc.) and age range they teach, so they can carry out practical science with confidence and knowledge of the underlying principles	% of schools
Schools where all teachers at post-16 level have a post-A level science qualification related to the science subject they teach (biology, chemistry, physics)	72%
Schools where all teachers at post-16 level have pedagogical training relevant to their specialist subject	55%
Schools where all teachers at pre-16 level, if they do not have a post-A level science qualification related to the subject they teach, have had sufficient additional training to give them the confidence and subject knowledge to conduct effective practical work at that level	27%
Schools where all science teachers have annual reviews of training and development needs in relation to practical science	34%
Schools where all science teachers have time for professional reflection with colleagues where so required	39%
Schools where all science teachers have regular training specific to practical science	22%

Benchmark 4: Frequent and varied practical science

Very few schools are able to meet the full benchmark for both frequency *and* variety. The frequency of practical science varies widely according to age and science subject, with greater frequency with younger age groups, and in physics and chemistry compared to biology. There is a strong correlation between subject specialist teachers and variety, suggesting specialist teachers do more varied practical work.

Qualitative interviews show mixed opinions about whether curriculum and assessment changes in England will help or hinder frequency and variety of practical science. Some say a more content-heavy curriculum will hinder it, but others say new assessment arrangements for GCSE and A level will help. See Benchmark 10 and Recommendation 5.

How frequently in practice?

The survey results show that the frequency of practical science varies widely according to age and science subject. Taking the results across the board, they suggest that around two-fifths of science lessons in English schools involve practical activities.

Other studies have explored this question using different approaches. Unpublished work from Durham University[47] suggests that over a quarter of lesson time at GCSE is spent on practical work. Wellcome's Science Education Tracker[48] found that a little under half of GCSE students reported doing hands-on practical work in science lessons at least once a fortnight, but three in ten reported doing it less than once a month or never.

So it looks as if most schools in England are falling short of the benchmark frequency, and that this is particularly so for older students taking examined courses.

In the light of our judgement that by international standards, English schools are well provided with laboratory facilities (see below), it is disappointing that many schools are not making full use of them.

Given universities' worries[49] about the practical skills of incoming students, infrequent practical science among post-16 students is a cause for concern.

BENCHMARK 4: FREQUENT AND VARIED PRACTICAL SCIENCE Students should experience a practical activity in at least half of their science lessons. These activities can be short, but should be varied in type	% of schools
Schools where on average, across the year and across all the sciences, at least half of lessons involve direct practical activities, whether hands-on or teacher demonstration	
– Key Stage 3 science	68%
– Key Stage 4 biology	33%
– Key Stage 4 chemistry	55%
– Key Stage 4 physics	47%
– Post-16 biology	15%
– Post-16 chemistry	28%
– Post-16 physics	24%
– Post-16 applied science	38%
Schools where all science lessons are at least 50 minutes long	88%
Schools where for practical activities over the course of the year all of the following are used: investigations, projects, collaborative research, experiments to confirm theory, experiments to show phenomena, and practising techniques	
– Pre-16 sciences	32%
– Post-16 sciences	34%

55%

The percentage of schools where at least half of Key Stage 4 (KS4) chemistry lessons involve direct practical activities.

28%

The percentage of schools where at least half of post-16 chemistry lessons involve direct practical activities.

Below: Melbourne Girls' College, Australia

Benchmark 5:
Laboratory facilities and equipment

This multi-faceted benchmark has nine separate criteria, and to achieve all of them is challenging even for the best-equipped school. Even so, this does not change our judgement that, by world standards, England is well provided with laboratory facilities. Looking in more detail at survey data, only 16% of respondents say that the availability of laboratories is very or quite often a barrier to practical science. When it comes to equipment, the situation is not so good, with only 42% of schools saying they have all the equipment they need. Qualitative interviews show the importance of lab design, and of consulting science staff from the start when designing or refurbishing labs.

16%

The percentage of schools that say the availability of laboratories is very or quite often a barrier to practical science.

BENCHMARK 5: LABORATORY FACILITIES AND EQUIPMENT Schools should have enough laboratories to make it possible for every teacher to do frequent practical science safely. Each laboratory should have sufficient equipment for students to work in small groups	% of schools
Schools where the availability of laboratories is never a barrier to carrying out practical activities in the science subjects taught	31%
Schools where all laboratories have sufficient space to safely accommodate the size of classes that will occupy them	40%
Schools where all laboratory space is flexible enough to allow students to work individually, in pairs and in small groups	43%
Schools where all laboratories have sufficient equipment to make it possible for teachers to do standard practical activities expected in their specialist subject at that level	42%
Schools where all laboratories give ready access to technology available to teachers to enable collection and analysis of digital data	27%
Schools that have a preparation space or spaces with well-organised, safe storage with easy access to laboratories	71%
Schools where all laboratories are accessible to students with any special educational needs and disabilities (SEND) encountered in the school	50%
Schools where all laboratory facilities are such that students can carry out extended practical science investigations (see Benchmark 8)	28%
Schools that have an accessible outdoor space where practical activities can take place	82%

Benchmark 6:
Technical support

Compared to many other countries, English schools are relatively well provided with support from technicians – with two-thirds of schools saying they have sufficient support in each science subject. But the qualitative interviews reveal unease at the difficulty in recruiting qualified and experienced technicians, the main reason being given as the low salary on offer. This is a concern because technicians are key enablers of other benchmarks (see *Prioritising benchmarks* in section 5.3).

Just over half of schools say all their technicians have regular opportunities for professional development – a larger proportion than for teachers, but still too few given technicians' complex responsibilities, which include health and safety.

BENCHMARK 6: TECHNICAL SUPPORT Science departments should have enough technical or technician support to enable teachers to carry out frequent and effective practical science	% of schools
Schools with sufficient specialist technical expertise to support practical work in each of biology, chemistry and physics	67%
Schools where all science technicians are given regular opportunities to have professional development	56%

67%

The percentage of schools with sufficient technical expertise to support practical work in each science subject.

56%

The percentage of schools that say all of their technicians have regular opportunities for professional development.

EXTENDED PROJECTS REMAIN AN ASPIRATION RATHER THAN A REALITY IN ENGLISH SCHOOLS

Above: Klosterschule, Germany

Benchmark 7: Real experiments, virtual enhancements

We looked for signs that schools are replacing hands-on practicals with computer simulations, and we found that 58% of schools use computers to replace practical 'little of the time' and 33% do so 'some of the time'.[50] This seems a reasonably healthy situation, but the level of training in digital technologies for science teachers is low. Also relevant is the finding for Benchmark 5 that only 27% of respondents say all their laboratories give ready access to technology enabling collection and analysis of digital data.

BENCHMARK 7: REAL EXPERIMENTS, VIRTUAL ENHANCEMENTS Teachers should use digital technologies to support and enhance practical experience, but not to replace it	% of schools
Schools that use virtual environments and simulated experiments to replace practical science experiences little of the time	58%
Schools where all science teachers have access to evidence about what works, in relation to digital technologies	18%
Schools where all science teachers have training in the use of digital technologies	17%

Benchmark 8: Investigative projects

Despite their benefits, extended projects remain an aspiration rather than a reality in English schools. In qualitative interviews, teachers told us that there is so much pressure on time, both in the formal curriculum and in co-curricular time, that such projects are a rarity in most schools. Schemes such as CREST[51] and Nuffield Research Placements[52] are valuable enablers, but the message is that extended projects will not become a majority activity until they are made a specified part of the school curriculum (Recommendation 6).

BENCHMARK 8: INVESTIGATIVE PROJECTS Students should have opportunities to do open-ended and extended investigative projects	% of schools
Schools where students have opportunities to do open-ended and extended investigative projects in science over the course of their school career	15%
Schools where laboratory facilities are such that students can carry out extended practical science investigations	28%

Benchmark 9: A balanced approach to risk

Three-quarters of respondents say all their teachers understand the shared responsibility for safety. This is something that *all* teachers need to understand, because although technicians are often expert in safety, they cannot control what happens in the classroom. It is a concern that all science teachers assess the risks and benefits for every practical activity, and act accordingly, in only 51% of schools.

We looked for signs that teachers, possibly under pressure from school management, are behaving in a risk-averse way and so limiting students' practical experiences. It's encouraging that when the benchmark is only slightly relaxed, 83% of respondents say 'all' or 'the vast majority' of teachers adopt a balanced and proportionate approach to managing risks and are supported by senior management in doing so. Stories of 'health and safety taking the heart out of science lessons' would seem to be mainly based on myth.

BENCHMARK 9: A BALANCED APPROACH TO RISK Students' experience of practical science should not be restricted by unnecessary risk aversion	% of schools
Schools where it is clearly understood that responsibility for safety is shared between the school or local authority as employer, the teacher and the technician:	
– By all science teachers	75%
– By all science technicians	79%
Schools that ensure access to authoritative and up-to-date guidance, including model risk assessments, is given:	
– To all science teachers	63%
– To all science technicians	85%
Schools where all science teachers assess the risks and benefits for every practical activity, and act accordingly	51%
Schools where a balanced and proportionate approach to managing risks, with support by senior management in doing so, is adopted by:	
– All science teachers	60%
– All science technicians	72%

51%

The percentage of schools where all teachers assess the risks and benefits for every practical activity and act accordingly.

83%

The percentage of schools that say 'all' or 'the vast majority' of teachers adopt a balanced and proportionate approach to managing risks and are supported by senior management in doing so.

Benchmark 10: Assessment fit for purpose

The majority (65%) of teachers regularly use practical science activities for formative assessment. A much smaller proportion use classroom assessment to give students a grade on their practical skills. However, this may change. With teachers required to 'endorse' practical activities at A level, increasing numbers of students are now receiving a pass or fail grade on their practical skills. Qualitative interviews suggest that the assessment arrangements at A level and GCSE introduced from 2015 and 2016 may be changing schools' approach to formative assessment lower down the school.

Several respondents mentioned the value of students having lab books in which they record their practical activities.

BENCHMARK 10: ASSESSMENT FIT FOR PURPOSE Assessment of students' work in science should include assessment of their practical knowledge, skills and behaviours. This applies to both formative and summative assessment	% of schools
Schools where teachers reflect on students' practical skills and knowledge when awarding a grade for science rated at 8 or above (using a scale of 1–10, where 1 is 'not at all' and 10 is 'fully and completely')	16%
Schools where teachers use practical activities as an opportunity very or quite regularly to formatively assess students' understanding of science	65%

Above: Organic synthesis at Raffles Institution, Singapore

5

MAKING PROGRESS TOWARDS THE BENCHMARKS

GOOD SCHOOLS ARE ALWAYS LOOKING FOR WAYS TO IMPROVE THEIR SCIENCE PROVISION, AND MANY ASPIRE TO BE WORLD CLASS

All schools will be able to make progress in some way towards the benchmarks and in this section we start to consider this in more detail, taking account of the potential costs of implementation, and where small amounts of investment might unlock substantial benefits.

5.1 THE COSTING EXERCISE

We commissioned consultants PwC to provide an analysis and commentary on the costs of meeting each benchmark. Their full report is online at **www.gatsby.org.uk/GoodPracticalScience**

PwC considered three main types of costs that schools will incur if they achieve all the benchmarks:

– The staff costs related to achieving and maintaining the benchmarks.

– Capital costs of facilities and equipment.

– Any additional expenses.

WE BELIEVE THAT PROGRESS CAN BEST BE MADE BY PRIORITISING BENCHMARKS 1, 3 AND 6 BECAUSE THESE THREE ARE STRONG ENABLERS FOR THE OTHER BENCHMARKS

PwC distinguished the one-off costs as schools undertake activities for the first time from the recurring costs. They considered whether the activities could be undertaken by schools reprioritising time spent on other activities rather than incurring additional expenditure.

PwC developed a school delivery model for practical science as the basis of their cost analysis. This model comprises a core team within the school science department led by the department head, who is accountable to a member of the senior leader team. The core team includes all science teachers and technicians.

PwC then used the Standard Cost Model (SCM)[53] to estimate the costs of the benchmarks. This involved using activity-based costing to break down each benchmark into its component activities, then analysing cost information for a small cross-section of six 'typical' schools, which PwC then extrapolated across all secondary schools in England.

PwC drew on a range of official statistics from the Office for National Statistics (ONS) and the DFE as well as other published research. They also organised two consultative workshops with teachers and technicians and consulted experts in the field of school laboratory design and supply. They were able to draw on the results of the school survey[54] to see what proportions of schools are already fully or partly achieving each benchmark.

There is a short commentary on costs for each benchmark in section 5.3, and details of all the costs and calculations are in the full costing report.

5.2 COSTING COMMENTARIES FOR EACH BENCHMARK

The costing exercise confirms that by far the greatest part of the cost of practical science is staff time, the large majority being teachers' time. The capital costs of laboratories and equipment are small by comparison. But if teachers were not doing practical science, they would be using some other kind of learning activity which would also need to be planned and delivered, so practical science does not represent substantial *additional* costs in teachers' time.

Benchmark 1: Planned practical science

We see this benchmark as a powerful enabler for most of the others. The costing report from PwC shows that the total amount of staff time required to undertake all the activities associated with Benchmark 1 is relatively small, and we believe this activity would not be burdensome, particularly once the policy has been set up in the first year. The school survey emphasises the value of having a senior leader as 'sponsor' for practical science.

Benchmark 2: Purposeful practical science

The costing report suggests that the total amount of staff time required to implement Benchmark 2 in full is significant, but lesson planning is something that good teachers will do anyway, whether it be a practical or any other activity. The important thing is that teachers are clear about why they are doing a practical activity, and what outcomes they want from it.

Benchmark 3: Expert teachers

The cost of paying a teacher is incurred by the school anyway, whether they are specialist or not, so the main costs in achieving this benchmark relate to recruiting teachers and developing their specialist knowledge.

As far as recruiting specialist science teachers is concerned, the reality is that for some schools, appointing (say) a physics specialist is impossible because none apply when the job is advertised. In such a situation headteachers may have to appoint a non-specialist and provide them with additional CPD to 'train them up' for the science that they will teach. Additional CPD of this kind helps build the teacher's confidence in practical work as well as their subject knowledge.

Benchmark 4: Frequent and varied practical science

The costing report points out that if a teacher is not doing practical science, they would be doing some other kind of activity, so there need not be a net increase in staff time required to meet this benchmark. Of course, practical activities displace other kinds of learning activities, but as we show in section 1.2, learning through practical activity has outcomes that other modes of learning do not.

Below: Viikki School, Finland

Benchmark 5: Laboratory facilities and equipment

The costing report shows that, unsurprisingly, the major cost in meeting this benchmark is the capital cost of building and equipping the laboratories in the first place. Once this has been achieved, the ongoing costs are the maintenance of facilities and equipment, and buying consumables such as chemicals. If the capital costs are considered on an annualised basis over an assumed 20-year lifetime, the cost of providing laboratories and equipment is £58 per student per year. While these costs are significant for hard-pressed school budgets, there seems little point in making small savings on consumables if it means the big capital investment in labs is not used to best effect. Having made the investment in laboratories, it makes sense to use them for the purpose for which they are intended.

Benchmark 6: Technical support

The costing report shows that using technicians rather than teachers to provide technical support represents a significant cost saving in meeting this benchmark. We have seen that countries that do not have technicians, such as Finland and the USA, have additional costs because teachers spend more time doing preparatory work that in the UK would be done by technicians. There is more about this in section 3.6.

PwC's analysis shows that for every 50 hours of technical support reallocated from a teacher to a technician, the school would save £1,400 on average.

Benchmark 7: Real experiments, virtual enhancements

The costing report finds that, if schools are meeting all the other nine benchmarks, they will have no additional costs in meeting this one.

Benchmark 8: Investigative projects

The overall cost of implementing this benchmark will depend on what proportion of students actually take up the opportunity to do a project. The costing report points out that the benchmark could be achieved by reallocating staff time from other 'out of school' activities, but of course this has whole-school implications.

Benchmark 9: A balanced approach to risk

The costing report assumes that the staff time needed to reach this benchmark is very small – though the benefits are very significant.

Benchmark 10: Assessment fit for purpose

The costing report shows that, relative to other benchmarks, this one is quite costly to achieve for schools that are currently doing no formative assessment of practical science. The cost is entirely in staff time. However, assessing students and providing them with feedback is part of good teaching of *any* kind, whether it is practical or not.

5.3 PRIORITISING BENCHMARKS

The survey data, with the qualitative interviews, suggest how the benchmarks might be prioritised to make progress on all of them. We believe that progress can best be made **by prioritising Benchmarks 1, 3 and 6**, because these three benchmarks are strong enablers for others (Figure 5).

The costing report from PwC reinforces this view. The recurring costs of achieving Benchmarks 1, 3 and 6 are all within reach, though we do not underestimate the practical difficulty of achieving them in the face of tight school budgets. Given that well over half of a school's budget goes on teaching staff, expenditure that enables teachers to do their job better is money well spent.

Schools that achieve Benchmark 1 (Planned practical science) have a policy for practical science which has been agreed by teachers, technicians and a member of the senior leader team, and is regularly reviewed. This policy isn't just about health and safety and use of labs: it is about the way teachers plan, deliver and assess their practical lessons and about the school's expectations of frequency and variety. The *process* of arriving at an agreed policy is at least as important as the policy itself, and enables the Head of Department to identify training and development needs in the year ahead.

The costing analysis shows that compared to some other benchmarks, this one should be relatively easy to achieve, especially once it has been set up in the first year.

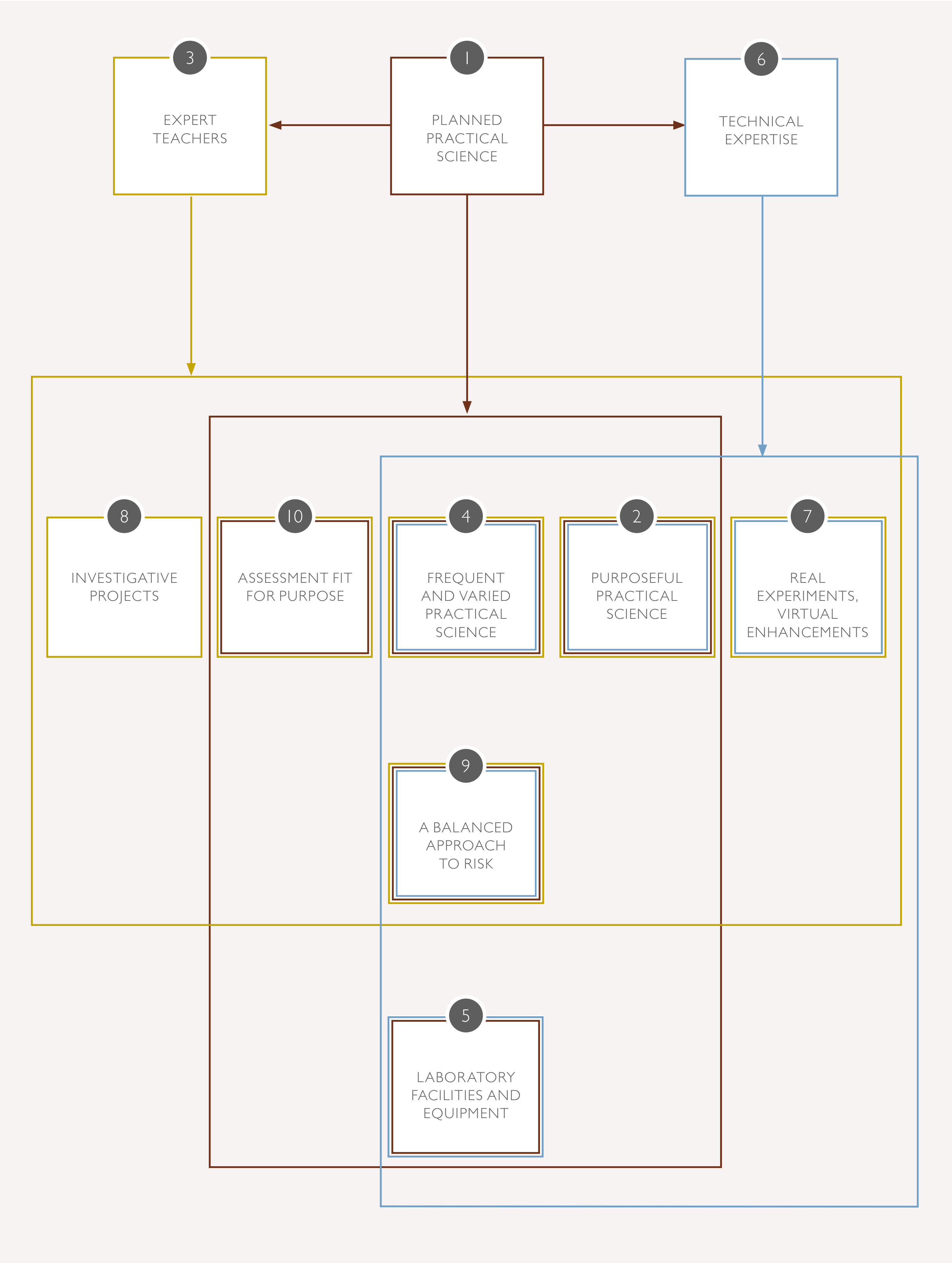
Schools that achieve Benchmark 3 (Expert teachers) have teachers with specialist science qualifications and regular professional development. Once this has been achieved, the other benchmarks are all much easier.

We are not pretending that this benchmark is easy to achieve. For most schools, achieving it will mean working and planning towards it over the long term, using a combination of succession planning, appointments of new staff and professional development of existing staff (Recommendation 7).

Schools that achieve Benchmark 6 (Technical support) have technicians with science-specific expertise and regular professional development. These technicians enable teachers to reach the other benchmarks by freeing up their time, by supporting less experienced teachers and by making the best use of existing laboratories and equipment. They can also support students undertaking extended investigative projects.

This benchmark is not easy to achieve, given the realities of school budgets and the vulnerability of 'ancillary' staff budgets. It is particularly important for senior leaders to appreciate the need for specialist *science* technicians, and to realise that doing without them is a false economy that increases the pressure on teachers.

Figure 5: Benchmarks 1, 3 and 6 are strong enablers



6

RECOMMENDATIONS

THIS SECTION HAS RECOMMENDATIONS FROM THE GATSBY FOUNDATION ABOUT HOW THE DELIVERY OF PRACTICAL SCIENCE, AS DEFINED BY OUR 10 BENCHMARKS, MIGHT BE IMPROVED

The 10 benchmarks for good practical science are for schools. The recommendations that follow are mostly for those that can impact on the wider education system in which a school operates, namely: teacher trainers, policymakers, Ofsted, government, teaching unions, professional bodies, and Ofqual.

This is a report about practical science and how to make it good. But it turns out that many of the things we advocate – such as expert teachers and planned lessons – make for good learning in *any* subject. So, several of our recommendations below are quite generic and would benefit science education across the board.

School leaders in England have a high level of autonomy by international standards. This gives them the flexibility to prioritise the 10 benchmarks and so achieve good practical science. But giving autonomy to schools does not relieve government of responsibilities. If schools are to achieve the benchmarks, government must:

– Fund them adequately.

– Secure and maintain the supply of expert teachers.

– Put in place a curriculum, assessment and accountability system that encourages good teaching.

These responsibilities are summarised in Figure 6.

> SCHOOLS, AND THE SCIENCE DEPARTMENTS WITHIN THEM, SHOULD BE FUNDED ADEQUATELY TO ENABLE THEM TO ACHIEVE THE BENCHMARKS

We have recommendations for government and policymakers (section 6.1) and for school leaders (section 6.2) – but our first recommendation is for both.

- All
- Government and policymakers
- School leaders and member bodies

RECOMMENDATION 1: THE 10 BENCHMARKS

To schools, policymakers, Ofsted and teacher trainers

We recommend Benchmarks 1–10 as defining the elements of good practical science in secondary schools. Schools should use them, policymakers should be guided by them, and teacher trainers and professional development leaders should use them to help shape their programmes. Ofsted should guide schools towards them if their science needs improvement.

Schools, and the science departments within them, should be funded adequately to enable them to achieve the benchmarks.

6.1 WHAT CAN GOVERNMENT AND POLICYMAKERS DO?

Secure and maintain the supply of expert teachers

RECOMMENDATION 2: TRAINING EXPERT TEACHERS

To government and teacher trainers

Secondary science initial teacher training (ITT) should have a strong subject-specific component relating to the science they will teach, especially its practical aspects. This should be reflected in the standards for Qualified Teacher Status (QTS), which should apply to teachers in all state-funded schools, including academies.

Government-funded Subject Knowledge Enhancement (SKE) courses for prospective science teachers should include sufficient laboratory time to develop practical skills. Courses that are only delivered online cannot provide this experience.

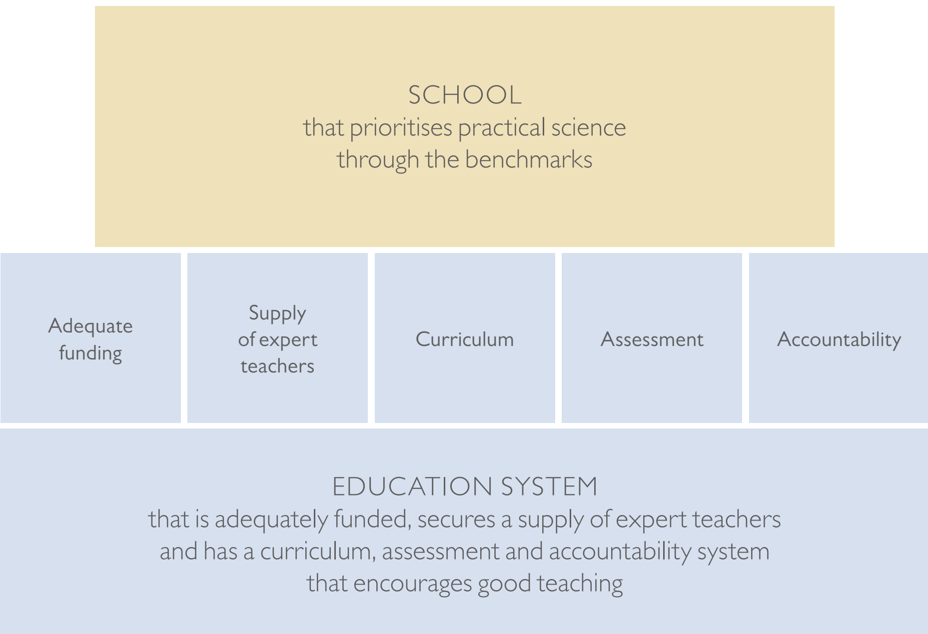
Government should ensure that the Teacher Supply Model (TSM) accurately forecasts the number of specialist teachers required.

Government should use the TSM to increase the number of specialist teachers in each of the sciences, through additional recruitment and through retention programmes, so that schools have enough high-quality applicants when they advertise posts.

The international evidence is clear across all schools and all subjects: the key to successful education is well-trained teachers. In the case of practical science, *subject* expertise is particularly important (Benchmark 3). It is for school leaders to decide the best way to recruit and train their specialist staff, but government needs to make sure that enough science specialists are being trained in the first place, and that they are being trained in the right things.

The ITT landscape in England is diverse. There have been calls[55] for government to identify a long-term strategic plan for ITT to address issues around teacher shortages and the range of ITT providers. We support these calls, noting that a plan like this could also look at the availability and uptake of subject-specific training.

Figure 6: For schools to exercise their autonomy, they must be built on a supporting education system



Within the subject-specific component, ITT should include a significant element relating to practical science, so that teachers begin their careers able to manage practical science safely and confidently.

We have seen, in countries such as Germany and Finland, the value of having a close relationship in ITT between university science departments and education departments. Now that DFE has unified responsibility for both schools and universities, it should explore the possibilities for closer collaboration of this kind in England, and see how it could be incentivised.

RECOMMENDATION 3: CONTINUING PROFESSIONAL DEVELOPMENT FOR TEACHERS

To government, teaching unions, professional bodies and other stakeholders

Over the next five years, England should move towards an embedded system of continuing professional development for teachers, with clear expectations of quantity and quality of CPD.

Teachers' CPD should have a strong subject-specific focus and in the case of science teachers it should include practical work wherever appropriate.

Benchmark 3 emphasises the importance not only of recruiting expert teachers but of developing their expertise through CPD. Even after initial training, teachers need to have their subject knowledge updated and to find new ideas for practical activities, including for example the use of digital technology to support practical science. This is important for their confidence as well as their skills and knowledge.

Teachers are often required to teach outside their first subject specialism and CPD can give them knowledge and confidence in a subject that may not be familiar to them. This is often the case for biology specialists, who are frequently asked to teach outside their specialism, but this should not prevent biologists from getting professional development in their own subject as well as outside it.

At present, uptake of science teachers' CPD in England is patchy, despite the availability of high-quality CPD, including through the National STEM Learning Centre and the network of Science Learning Partnerships.[56] This is true for all subjects, not only science, and will remain true until England has an embedded system of CPD in which there are clear expectations of the quantity and quality of professional development that a teacher will receive during their career – as there is in countries such as Singapore, Finland and Scotland. The Chartered College of Teaching could have a key role in bringing this about.

A curriculum, assessment and accountability system that encourages good teaching

RECOMMENDATION 4: ACCOUNTABILITY AND PRACTICAL SCIENCE

To government

Government should review accountability measures compared with other nations, to assess how they could give teachers more autonomy and freedom to innovate in the way they teach, particularly in the case of practical science.

To Ofsted

When inspecting school science departments, Ofsted should take particular note of the quality and frequency of practical science, and record it in the report on the school.

Most of the countries we visited give teachers wide autonomy over the way they teach, leading to innovation and diversity. In England, autonomy is often constrained by teachers looking for 'what Ofsted wants', and by pressure from school leaders to maximise exam performance.

The assessment system in England influences teachers' behaviour more strongly than in any other country we have seen. While several countries have high-stakes assessment for school leavers at age 18, none has the equivalent of GCSE, preparation for which can dominate throughout years 10 and 11. This reduces the amount of time that schools can spend on practical science, as the tempo of exam preparation increases as GCSEs approach.

RECOMMENDATION 5: VALID ASSESSMENT

To government and Ofqual

Government and Ofqual should monitor current arrangements for assessment of practical science at GCSE and A level to check their impact on the quality and frequency of practical science. If negative effects are found, changes should be made.

To research funders

Research should be done into valid, reliable and manageable ways of assessing practical science, in particular where assessment is indirect and by means of written questions.

Benchmark 10 is about assessment of practical science, but when it comes to external exams such as GCSE and A level, teachers have limited control over what goes on, because the rules are laid down by Ofqual and the Awarding Organisations.

The introduction of new arrangements for practical science assessment at GCSE (in 2016) and A level (in 2015) has been controversial. The intention of Ofqual and the Awarding Organisations is to give schools more freedom to engage students with a wider range of practical activities.[57] But when these proposals were made, many within the science community feared that with practical science no longer contributing to the overall grade, there was a risk of undermining the teaching of practicals in schools.[58] It will take time for the effects to become apparent, but the situation needs careful monitoring. The Gatsby Foundation, with Wellcome, is funding a three-year study by Durham University[59] to see what changes may be happening in schools as a result of these new arrangements.

Assessment organisations, in this country and overseas, commonly use written questions to assess practical science[60] rather than direct assessment of students' practical activities. Yet little is known about the validity of written assessment of practical skills. Given how effective teachers can be at coaching students to do well in written tests, we need to know more about what valid written assessments look like. Wellcome, with the Gatsby Foundation and the Royal Society, is funding *Assessing Practical Science Skills in Schools and Colleges*[61] to stimulate research into the best ways to assess students' practical science skills. The results could be used to inform longer-term GCSE and A level reform.

Seen internationally, it is remarkable how little trust the system in England places in teachers to make reliable and unbiased assessments of their students' achievements. In all the countries we visited, it was uncontroversial that teachers should assess their students for external as well as internal purposes, and it was firmly believed that when it comes to practical science, direct assessment by teachers is the most valid method. This should be the direction of travel in England too, though we realise there is a long way to go.

> MOST OF THE COUNTRIES WE VISITED GIVE TEACHERS WIDE AUTONOMY OVER THE WAY THEY TEACH, LEADING TO INNOVATION AND DIVERSITY

RECOMMENDATION 6: PROJECTS IN THE CURRICULUM

To government and Ofqual

The curriculum should evolve to include more requirements for extended projects in investigative science. In particular, an extended project should become an embedded, compulsory part of post-16 study for all students on pre-university courses. For those studying a majority of science subjects, the project should have a science focus.

Our experiences in the UK and other countries suggest that an extended project can offer unique opportunities for students to develop skills and attitudes that are not developed by more constrained activities. Benchmark 8 calls for students to have opportunities to do open-ended and extended investigative projects in science, but the school survey shows how difficult this is to achieve in practice.

There are things that schools can do to encourage science projects (section 3.8), but in the end we believe that systemic change to embed projects in the core curriculum is needed to bring about a radical increase in project work, and this is the thinking behind Recommendation 6. We particularly recommend the model of the *profielwerkstuk* in the Netherlands. We also note that an independent research project[62] is a respected core feature of the International Baccalaureate. Until the A level assessment regulations were changed in 2015, an extended Individual Investigation was a successful part of the Salters Advanced Chemistry programme in the UK.

We also believe that universities can do more to support students' science projects, as we saw in several countries. We see opportunities for showcasing the best of students' projects, through the UK's *Big Bang* science and engineering fairs[63] but also through events that could be held in science museums and science centres, as we saw in Australia.

6.2 WHAT SCHOOLS CAN DO

Our benchmarks show what schools need to do to get good practical science. We have three specific recommendations to speed schools on their way.

Investing in expert people

RECOMMENDATION 7: RECRUITING, RETAINING AND DEPLOYING SPECIALIST TEACHERS

To school governors, headteachers and science leaders

Schools should take a strategic approach, using a combination of shrewd recruitment, retention measures and CPD, to get a better proportion of science subject specialists in their science team. Where subject specialists are scarce, they should teach within their specialism where possible, and schools should take a strategic approach to deciding which classes and age groups to use them with.

To science professional bodies and funders

A study should be commissioned to produce practical recommendations for schools on how to achieve the above. The result of this study would be a practical guide for schools, illustrated with case studies, on how they can get a better proportion of science subject specialists, and how best to deploy them.

For many schools, the reality is that science subject specialists are very hard to recruit, especially in physics. In such cases, having a long-term plan can help. Even in difficult circumstances, schools can plan for how to improve their teaching team's subject expertise, using a combination of shrewd recruitment and planned continuing professional development (CPD).

In England, government funds CPD programmes for teachers wanting to extend their subject specialism to include, for example, physics.[64]

> TECHNICAL SUPPORT SAVES TEACHERS' TIME AND IMPROVES SCIENCE DEPARTMENT MORALE. REDUCING TECHNICIANS' CONTRACTED TIME IS A FALSE ECONOMY BECAUSE IT INCREASES THE LOAD ON TEACHERS

Maintaining a strong subject specialist team is as much about retention as recruitment. If schools can retain their good specialist teachers, they won't need to recruit new ones. There is evidence[65] that giving teachers ready access to CPD pays off in retention.

CPD does not necessarily have to involve going out of school. In Singapore and Massachusetts, we saw examples of schools' professional learning communities, which gave teachers dedicated time to reflect together on the way they teach.

RECOMMENDATION 8: VALUING SCIENCE TECHNICIANS

To school governors, headteachers and science leaders

Technicians should be valued as an integral part of the science department.

They should be given professional development opportunities to refresh their professional skills and their expertise in health and safety, and to give them new ideas for practical science.

They should have opportunities to get professional recognition through Registered Science Technician (RSciTech) and Registered Scientist (RSci).

Benchmark 6 is about providing technical support for practical science. In section 3.6 we describe how technical support saves teachers' time and improves science department morale. Reducing technicians' contracted time is a false economy because it increases the load on teachers.

Schools should recognise the expertise of technicians and offer them opportunities to develop their role, for example by working directly with students in the laboratory and in STEM Clubs, and on extended projects.

Planning for practical science

RECOMMENDATION 9: PLANNING FOR SUCCESS

To the Association for Science Education and science professional bodies

Drawing on the experience of schools, guidance should be produced on how to go about developing a written policy for practical science.

We see Benchmark 1, *Planned practical science*, as a cornerstone for good practical science, but the school survey shows that only a minority of schools have a written policy for practical sciences as the benchmark suggests they should.

We believe schools may find it helpful to have guidance on how to go about producing a policy, bearing in mind that the *process* of producing the policy, collectively as a science department, is as valuable as the policy itself. We encourage the Association for Science Education and science professional bodies to produce and distribute this guidance, which should be developed and piloted with a range of schools.

RECOMMENDATION 10: MANAGING RISKS

To school governors, headteachers and science leaders

All schools in England should belong to CLEAPSS, either individually or through their local authority or Academy Trust, and should use its expert advice to ensure a balanced approach to risk.

Benchmark 9 says teachers and technicians should adopt a balanced and proportionate approach to managing risks, and be supported by senior management in doing so. The best way to help this happen is for the school to follow expert advice from CLEAPSS, the school laboratory safety organisation, which has a track record of a responsible approach to safety combined with avoiding unnecessary risk aversion. CLEAPSS's advice is widely acknowledged as representing best practice.

Most schools in England are already members of CLEAPSS, either individually or through their local authority or academy trust. Every school should be, and should follow CLEAPSS's pragmatic advice. CLEAPSS covers Wales and Northern Ireland as well as England. In Scotland, a similar role is performed by SSERC. All UK schools should belong to CLEAPSS or SSERC.

7

CONCLUSION

Experiments are the essence of science and the appeal of practical science is the reason many scientists, engineers and technicians chose the career they did. But in a world where schools are under intense pressure to perform well in written exams, practical science is at risk.

Our study has shown that many of the ingredients of good practical science are the ingredients of all good science learning – expert teachers, well-planned lessons and technical support.

Government needs to create the right environment, with adequate funding for schools, a good supply of trained specialist teachers and an accountability system that encourages learning beyond exams alone. But in the end it is for headteachers and science heads to take the lead in prioritising practical science – and our benchmarks show what they need to do to get practical science that is world class. By achieving that, they will engage students, whether or not they pursue science in the future, in the essence of what it is to be a scientist.

ENDNOTES

1 *Practical skills of new undergraduates* (May 2011). Russell Group survey, Laura Grant Associates for the Gatsby Charitable Foundation. www.gatsby.org.uk/uploads/education/reports/pdf/practical-skills-of-new-undergraduates-report-on-research-workshops-laura-grantoct-2011.pdf (accessed June 2017).

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3 *Practical work in school science: a report and proposal for a strategic framework, SCORE* (2008). *Benchmarks for secondary schools*, SCORE (April 2013).

4 *Getting Practical, the Association for Science Education* (2009). www.ase.org.uk/professional-development/getting-practical (accessed April 2017).

5 At the time of the preliminary survey, only the PISA 2012 results were available. Since then PISA 2015 has been published, and other PISA references in this report are aligned to PISA 2015.

6 *Getting Practical, the Association for Science Education* (2009). www.ase.org.uk/professional-development/getting-practical (accessed April 2017).

7 The Programme for International Student Assessment (PISA) is an international comparative study organised by the Organisation for Economic Co-operation and Development (OECD). See PISA 2015 Science Framework, in *PISA 2015 Assessment and Analytical Framework: Science, Reading, Mathematic and Financial Literacy* (2015). OECD Publishing, Paris.

8 PISA defines procedural and epistemic knowledge as 'knowledge of how ideas about the natural world are produced by scientists, and an understanding of the goal of scientific inquiry and of the nature of scientific claims'.

9 In PISA 2015, 'inquiry-based instruction' includes a number of elements – several related to practical science.

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11 The Science Education Tracker constructed a Family Science Connection Index (FSCI) to measure the strength of young people's family science networks.

12 As defined by the Income Deprivation Affecting Children Index (IDACI) and/or Free School Meal entitlement.

13 'Science capital' refers to science-related qualifications, understanding, knowledge (about science and 'how it works'), interest and social contacts (e.g. knowing someone who works in a science-related job). ASPIRES. *Science and career aspirations: age 10–14*. Kings College London (2013).

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17 *Good Career Guidance* (2014). The Gatsby Foundation. www.gatsby.org.uk/education/programmes/good-career-guidance (accessed April 2017).

18 The Programme for International Student Assessment (PISA) is an international comparative study organised by the Organisation for Economic Co-operation and Development (OECD). See PISA 2015 Science Framework, in *PISA 2015 Assessment and Analytical Framework: Science, Reading, Mathematic and Financial Literacy* (2015). OECD Publishing, Paris.

19 In some cases, we selected specific states within a country, such as Massachusetts in the USA, and Victoria in Australia, on the basis of their known international performance.

20 In the Netherlands, VWO schools are pre-university, and HAVO schools are general academic.

21 For example Millar. R. (2010). *Analysing practical science activities to assess and improve their effectiveness.* Hatfield: Association for Science Education.

22 STEM Clubs are clubs that give students opportunities to do science, technology, engineering and mathematics activities outside the formal curriculum. Advice and support on setting up STEM Clubs is available from the National STEM Learning Centre www.stem.org.uk/stem-clubs (accessed April 2017).

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24 Young people's views on science education, Wellcome Trust. (2017). *Wellcome Science Education Tracker, 2016*. www.wellcome.ac.uk/sites/default/files/science-education-tracker-report-feb17.pdf (accessed April 2017).

25 The Gatsby Foundation considers a relevant 'post-A level' science qualification to be (1) a degree relevant to the specialist subject to be taught (biology, physics or chemistry) or (2) a Subject Knowledge Enhancement (SKE) course or industry experience plus a teaching qualification (such as a postgraduate certificate in education) in the specialist subject to be taught.

26 Science Learning Partnerships use local expertise in teaching and learning science to facilitate CPD and provide school-to-school support www.stem.org.uk/science-learning-partnerships (accessed June 2017).

27 ENTHUSE bursaries contribute towards the costs of CPD at the National STEM Learning Centre for all UK state-funded schools and colleges www.stem.org.uk/bursaries (accessed June 2017).

28 G14 *Designing and planning laboratories,* CLEAPSS (2009). *School Science Accommodation*, Gratnells and ASE (2015). *Science Accommodation in Secondary Schools* (Building Bulletin 80), Department for Education (2004). *Building Bulletin 103*, Department for Education (2014). *Benchmarks for secondary schools*, SCORE (April 2013).

29 CLEAPSS is a national organisation that provides expert advice on school laboratories and laboratory safety.

30 There is a summary of authoritative sources of advice at www.ase.org.uk/resources/lab-design (accessed April 2017).

31 In Scotland, the Scottish Negotiating Committee for Teachers (SNCT) recommends a maximum class size of 20 for the teaching of practical classes (including science) in secondary school. While this is not a legal requirement, it is widely accepted by Scottish local authorities and included in their agreements with schools www.snct.org.uk/wiki/index.php?title=Appendix_2.9#PRACTICAL_CLASSES (accessed August 2017).

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38 The Royal Society's Partnership Grants of up to £3,000 are available to schools to enable students, aged 5–18, to carry out science, technology, engineering or mathematics (STEM) projects www.royalsociety.org/grants-schemes-awards/grants/partnership-grants (accessed May 2017).

39 The CREST scheme, run by the British Science Association, provides a framework for extended science projects at gold, silver and bronze levels www.crestawards.org (accessed April 2017).

40 Nuffield Research Placements provide students with opportunities to work alongside professional scientists, technologists, engineers and mathematicians www.nuffieldfoundation.org/nuffield-research-placements (accessed May 2017).

41 Institute for Research in Schools www.researchinschools.org (accessed April 2017).

42 Health and Safety at Work Act, 1974.

43 Judith Hackitt, Chair, Health and Safety Executive. *A View from the Top.* Royal Academy of Engineering (March 2016).

44 CLEAPSS is a national organisation that provides expert advice on school laboratories and laboratory safety.

45 SSERC provides, among other services, advice on laboratories and safety in Scotland. All Scottish state schools are eligible through their local authority.

46 From OCR www.cambridgeassessment.org.uk/Images/138094-a-report-on-perceptions-of-current-practical-assessment-in-science-gcses-and-igcses.pdf (accessed August 2017).

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50 Pye Tait report, Appendix 4. www.gatsby.org.uk/goodpracticalscience

51 The CREST scheme, run by the British Science Association, provides a framework for extended science projects at gold, silver and bronze levels www.crestawards.org (accessed April 2017).

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53 The SCM is based on extensive international experience and has been widely used by the UK Government and other governments to assess the costs (and benefits) of new and existing policy.

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APPENDICES

APPENDIX 1
THE RAPID EVIDENCE ASSESSMENT

APPENDIX 2
REPORT FROM THE PRELIMINARY SURVEY

APPENDIX 3
REPORTS FROM THE OVERSEAS VISITS

APPENDIX 4
THE SCHOOL SURVEY

APPENDIX 5
CONTRIBUTORS AND CONSULTEES

Appendices and the costing report commissioned from PricewaterhouseCoopers are available to view at www.gatsby.org.uk/GoodPracticalScience

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