Beyond 2020: ten questions for science education

Michael J. Reiss

Abstract The 1998 Nuffield Foundation report *Beyond 2000: Science Education for the Future*, by Robin Millar and Jonathan Osborne, produced ten recommendations and had a major effect on curriculum development in England, Wales and Northern Ireland. Twenty years after its publication, I pose ten questions for science education. The hope is that these will contribute to the current debate as to what a school science education should consist of and help to lead to an improved science education beyond 2020.

Background

Back in 1998, Robin Millar and Jonathan Osborne produced a report of a series of seminars and open meetings funded by the Nuffield Foundation entitled *Beyond 2000: Science Education for the Future* (Millar and Osborne, 1998). The report became very widely cited and extremely influential. In it, Millar and Osborne sought to provide a new vision of an education in science. In words that seem as relevant today as when they were penned, some 20 years ago, they wrote:

> *Education, at the end of the 20th century, no longer prepares individuals for secure, lifelong employment in local industry or services. Rather, the rapid pace of technological change and the globalisation of the marketplace have resulted in a need for individuals who have a broad general education, good communication skills, adaptability and a commitment to lifelong learning. Our view is that the form of science education we currently offer to young people is outmoded, and fundamentally is still a preparatory education for our future scientists. An advanced technological society such as ours will always require a supply of well-qualified research scientists, but this requirement will be met, as at present, by educating and training only a small minority of the population. On the other hand, the ever-growing importance of scientific issues in our daily lives demands a populace who have sufficient knowledge and understanding to follow science and scientific debates with interest, and to engage with the issues science and technology poses – both for them individually, and for our society as a whole. Without a fundamental review and reconsideration of the aims and content of the science curriculum, what we offer our young people is in danger of becoming increasingly irrelevant both to their needs and those of society.* (Millar and Osborne, 1998: 1)

The first recommendation of *Beyond 2000* was that:

> *The science curriculum from 5 to 16 should be seen primarily as a course to enhance general 'scientific literacy'* (Millar and Osborne, 1998: 9)

This led onto the report's second recommendation:

> *At Key Stage 4, the structure of the science curriculum needs to differentiate more explicitly between those elements designed to enhance 'scientific literacy', and those designed as the early stages of a specialist training in science, so that the requirement for the latter does not come to distort the former.* (Millar and Osborne, 1998: 10)

These recommendations had major ramifications. They led to the award of a grant from the Qualifications and Curriculum Authority in 2000 to John Holman, Robin Millar and myself to devise a more flexible curriculum structure at key stage 4 (that is, ages 14–16, years 10 and 11 in England, Wales and Northern Ireland) that would indeed enable such a differentiated science curriculum. With contributions from Andrew Hunt and others, the result was that for a decade the large majority of key stage 4 students took a course of core science (equivalent to a single GCSE) and also a course of additional science or (less commonly) applied science (each also equivalent to a single GCSE).

Now, in 2018, the wheel has gone more than full circle. Applied science at GCSE no longer exists and the very concept of balanced science from ages 5 to 16 for all has been eroded as science has been split into biology, chemistry and physics, with some students dropping one or even two of these at age 14. Some students, typically from advantaged backgrounds, study all three sciences to GCSE ('Triple Science') while the majority are entered for courses that are considered by many to prepare them less well for post-16 sciences.

At the same time, the frenetic pace of government-imposed curriculum development in England, which led Ted Wragg memorably to coin the phrase 'Mad Curriculum Disease' (Wragg, 1991), has, for once, slowed. This is allowing the science education community to take a longer and more fundamental look at what the 5–16/19 science curriculum should look like.

Questions for science education

Beyond 2000 made ten recommendations, of which the first two have been cited above. My aim is a more modest one – namely to propose ten questions for science education. As with *Beyond 2000*, my principal focus is the UK (education in Scotland is, of course, distinct from that in the other three UK nations) although the questions apply more widely. Some of these questions are already actively being debated; my hope is that together these ten questions will help lead to an improved science education post-2020. There are other questions that could be proposed – I don't discuss issues to do with initial teacher education, continuing professional development or textbooks – but these ten are enough to be getting on with.

Question 1: What should be the aims for science education?

There currently exist a multiplicity of aims for school science education, though these are often implicit. Governments and industry frequently focus on the needs for more scientists and for those who, while not scientists, use science in their work. *Beyond 2000* rejected this as the principal aim for school science education. It argued instead, that 5–16 science should principally aim to enhance scientific literacy for all students. A number of authors have argued that school science education should promote social justice (e.g. Calabrese Barton, 2001). More recently, John White and I have argued that it should promote flourishing, that is that it should equip each learner to lead a personally fulfilling life and help others to do so (Reiss and White, 2014).

The intention here is not to provide answers to the question of what the aims of science education should be but to suggest that unless *some* degree of consensus is reached it will be difficult to provide stable curricula that garner widespread support. Given that the overwhelming majority of students taking A-levels in the UK go on to university, it is relatively easy to defend the assertion that either 'the' or, at any rate, 'a main' function of A-levels should be to prepare students for university entry. However, for earlier age groups this question is a harder one to resolve.

Question 2: At what age should we no longer have a common science curriculum?

When O-levels were introduced in 1951 in England, Wales and Northern Ireland as a replacement for the School Certificate, the presumption was that only a small proportion (perhaps 20%) of each cohort would sit them and that no other examination at age 16 was needed. In 1961, however, Certificates of Secondary Education (CSEs) were introduced, intended for the next 40% of the ability range of each cohort. The two systems, O-levels and CSEs, then sat side by side until 1988 when General Certificates of Secondary Education (GCSEs) were introduced.

The introduction of GCSEs in 1988 therefore meant that the large majority of students studying science at age 16 were entered for the same qualification. Furthermore, at this time, also more or less the time of the start of the National Curriculum in 1989, there was widespread acceptance that the large majority of students should study Double Award Science in 20% of curriculum time. This meant that they obtained two GCSEs, both of the same grade, for a balanced science course that, while dominated by equal amounts of biology, chemistry and physics, contained more earth science than today's GCSEs in biology, chemistry and physics do.

Beyond 2000 helped put an end to this 'one size fits all' approach. The introduction in 2006 of core, additional and applied science meant that differentiation now started at age 14 rather than 16. The hope, of course, was that this would allow for courses that were more motivating – a common argument for differentiation in a market place. Unfortunately, it is unclear whether these courses were more motivating and, if so, to whom. It is the case that their introduction more or less coincided with an increase in the numbers choosing to study the sciences post-16, but it is difficult to attribute causation. However, what is clear from research undertaken at the University of Leeds is that, far from increasing social mobility (one of the stated aims of the 2006 science education curriculum reforms), if anything the opposite proved to be the case (Homer, Ryder and Donnelly, 2013). This is not surprising. Triple Award Science has always been seen as higher status (e.g. Reiss, 2000) and parents from higher socio-economic backgrounds are more likely to be able to be able to effect agency in ensuring their children get to take such higher status courses.

The ending of core, additional and applied science courses at GCSE has not put an end to differentiation at age 14, as government pressure to increase the number of students taking Triple Award science has continued to mean that there is more heterogeneity in curriculum offers than there was back when GCSEs were introduced. Of course, some countries, for example Germany and Switzerland, operate a form of differentiation from the start of secondary schooling, a system with some similarities to the one introduced in England as a result of the 1944 Education Act.

Question 3: How should the science curriculum be organised and what should be the balance between biology, chemistry and physics?

One of the major innovations of the science National Curriculum when it was introduced in 1989 was that it was arranged into 17 Attainment Targets (the 1988 draft was even more ambitious with 22 Attainment Targets). Some of these could unambiguously be allocated to the domains of biology, chemistry and physics, and, indeed, in subsequent revisions, they were. Others, however, cut across these three domains, notably AT1 'Exploration of science (knowledge and understanding of science communication and the application and implications of science)' and AT17 'The nature of science'.

While AT17 as a separate Attainment Target soon fell by the wayside, it survived in combination with AT1 in its various incarnations and an attenuated version exists to this day. As a member of the National Curriculum Review Science Working Group (2011–13), I can attest to the fact that government ministers were suspicious of anything to do with the nature of science. The way in which science reaches its conclusions and its scope were regarded as unproblematic. Science educators, though, tend to want more time to be spent on such questions, believing that this will give students a better understanding of the power, scope and limitations of science (cf. Kind and Osborne, 2017).

Beyond 2000 advocated that the science curriculum be presented as 'Explanatory stories', arguing that:

> *science education should make much greater use of one of the world's most powerful and pervasive ways of communicating ideas – the narrative form – by recognising that its central aim is to present a series of 'explanatory stories'. By this we mean that science has an account to offer in response to such questions as 'How do we catch diseases?', 'How old is the Earth and how did it come to be?', 'How come there is such inordinate variety of living things here on Earth?' It is these accounts ('explanatory stories') and their broad features which interest and engage pupils and, therefore, it is these accounts that any science curriculum needs to keep firmly in its sights and as its curriculum aims.* (Millar and Osborne, 1998: 13)

The science education innovation that has most built on the idea of explanatory stories is that of 'Big Ideas', driven forward by Wynne Harlen (Harlen *et al*., 2010, 2015). These two reports have been translated into a number of languages and have had major effects on the science curricula of a number of countries. In Chile, for example, the entire science curriculum has been rewritten within a 'Big Ideas' framework.

Finally, in this section, a heretical question. What should be the balance between biology, chemistry and physics in terms of the time devoted to them in the various years of schooling? The National Curriculum presumes that the time is split equally among them each and every year. But one wonders if this really is best.

Question 4: How should the science curriculum engage with other subjects?

Almost all countries construct their school curricula, certainly for older students, on the basis of subjects. There are advantages to this. For many teachers, particularly at secondary level, their subject specialism is an important aspect of their professional identity. In addition, constructing curricula on the basis of subjects means that students are more likely to be taught by those with subject-specific expertise. Of course, younger students, in primary schools, may be taught several, or even all, of their subjects by the same teacher.

In any event, however many teachers any individual student has, the question remains as to how the science curriculum deals with other subjects. One possibility is that, aside from drawing on English and mathematics, the science curriculum makes no reference to other subjects, remaining hermetically sealed from them. Another possibility is that an expanded science curriculum includes within itself portions of history, moral philosophy and design and technology as these are wanted – for example, for teaching about the origins of the periodic table, the ethics of genetic engineering and the uses of electronics. A further possibility is that, while it is not envisaged that students are taught aspects of other subjects by their science teachers, the curriculum has extensive cross-referencing to other subjects.

Each of these possibilities has advantages and disadvantages, which is why I regard the question as an open one. It is also quite an important one. If students fail to see how science connects with other subjects, they may fail to see its relevance. For many students, this is likely to be demotivating, though we should always remember that there is an important minority of students – well represented, I suspect, among professional scientists and readers of *School Science Review* – for whom such links with other subjects, especially arts and humanities subjects, would be unlikely to add to their interest in science.

Question 5: How can school science address issues of student disadvantage?

When I taught science in schools, I had a rather naïve notion that, while success in certain subjects, for example

English literature and music (with its emphasis at the time on the classical tradition), might be likely to relate quite closely to home background, this would be less the case in science. I was mistaken (Gorard and See, 2009). Success in school science is at least as socially stratified as in English and mathematics.

The most sustained study in England on the importance of home background for science engagement and attainment is the long-running ASPIRES project (Archer *et al*., 2013; www.ucl.ac.uk/ioe/departments-centres/departments/education-practice-and-society/aspires). A central finding of this project is that a key factor affecting the likelihood of a student aspiring to a science-related career by the age of 14 is the amount of 'science capital' they have. Science capital is a term that derives from Bourdieu's notion of cultural capital. Cultural capital is gained mostly through social learning and constitutes people's symbolic and informational resources for action. What the ASPIRES project did was to focus on science capital as a resource that enables individuals to feel comfortable about science and to desire to access it. Of course, individuals vary greatly in their science capital. If you are a young person whose parents or other family members have never taken you to a science museum, have no interest in watching science programmes on TV and have never bought you a book about science, let alone a chemistry set or microscope, chances are you score low on any measure of science capital.

Of course, this does not mean that the amount of science capital a family has is a given, nor that the relationship between science capital and aspirations is necessarily deterministic. Families, and students within them, have agency and can overcome disadvantage (Gokpinar and Reiss, 2016) and science capital can be built in the classroom (Nomikou, Archer and King, 2017). The Royal Society of Chemistry is currently funding a five-year intervention study, Chemistry for All (www.rsc.org/campaigning-outreach/outreach/scientists/chemistry-for-all), to see whether disadvantage can be overcome. The hope is that more students from disadvantaged backgrounds will choose to study chemistry in higher education.

Question 6: What pedagogies are most effective?

Curricula are important but common sense suggests that given a choice between an excellent curriculum and mediocre teaching on the one hand and a mediocre curriculum and excellent teaching on the other, the latter wins hands-down. In this case, common sense is supported by the research evidence. Hattie (2012), after an exhaustive review of the research evidence, produced a league table of 150 factors and their effects on learning. The factors were arranged in terms of decreasing 'effect sizes' (ES), where an effect size of 1 is roughly equivalent to increasing the rate of learning by 50% (e.g. two grades better at GCSE). Hattie's top 10 factors are as follows:

1. Self-reported grades (ES = 1.44) – Hattie now calls this 'student expectations', enabling students to do better than they think they are going to do.
2. Piagetian programmes (ES = 1.28) (e.g. CASE www.kcl.ac.uk/sspp/departments/education/research/Research-Centres/crestem/Research/Past-Projects/Cognaccel.aspx).
3. Early interventions to prevent academic failure (ES = 1.07) (e.g. Reading Recovery www.ucl.ac.uk/international-literacy/reading-recovery).
4. Teacher credibility (ES = 0.90).
5. Providing formative evaluation (ES = 0.90).
6. Micro teaching (ES = 0.88).
7. Classroom discussion (ES = 0.82).
8. Comprehensive interventions for SEN students (ES = 0.77).
9. Teacher clarity (ES = 0.75).
10. Feedback (ES = 0.75).

The simplest way of summarising these top 10 factors is that what teachers do in their classrooms is of most importance in increasing student attainment. Of course, good pedagogies can be facilitated by good curricula.

Most of the entries in Hattie's list are uncontroversial. One of the genuine controversies within science education is the value of teaching in ways that start with the contexts of science. In England, and a number of other countries, this approach is associated with the Salters' Company, one of the City of London Livery Companies. For a number of decades, and starting with Salters' GCSE Chemistry, the Salters' Company has funded a number of context-based courses, devised in partnership with the University of York Science Education Group.

Those in favour of context-based approaches to the teaching of science say that this motivates students, enabling them to see the relevance of what they are doing. Those who are not in favour fear that it detracts from the science. Although a systematic review (Bennett, Lubben and Hogarth, 2007) concluded that context-based approaches resulted in more positive attitudes to science in both girls and boys and reduced the gender differences in attitude, the number of high-quality studies available to the review was small and none was undertaken after the year 2000. Perhaps more importantly, almost no studies ever randomly allocate students to context-based versus non-context-based teaching. It seems possible that the review's conclusions tell us more about teachers who choose to teach using contexts than about any direct effects on students.

Question 7: How can best use be made of practical work?

Practical work is a defining characteristic of much of science. Despite this, how it should be used within school science remains controversial. In this journal, Osborne (2015) has argued that its role in science is over-emphasised and misunderstood. Characterising practical work as 'doing' science, Osborne argues that this is only one of five pedagogic approaches required for the teaching of science, the others being 'talking', 'writing', 'reading' and 'representing' science.

Osborne is not alone. Scepticism as to the effectiveness of the laboratory-centred approach to science teaching has led many researchers (e.g. Hodson, 1996; Abrahams and Millar, 2008) to question the effectiveness of practical work and to consider how best to make it most effective. One of the key findings of research is that, while students quite often are able to *do* what their teachers want them to when undertaking practical work, they much less often show any understanding as to *why* they are doing what they are doing.

In a recent major review on good practical science for the Gatsby Charitable Foundation, Holman (2017) concluded 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 examinations alone. But, in the end, it is for head teachers and heads of science to take the lead in prioritising practical science. Holman went on to present a set of benchmarks to allow schools to determine the quality of the practical science that they are providing.

Question 8: How can new technologies be used to best effect in science education?

Despite decades of enthusiasm for the use of new (digital) technologies in school science education, the potential remains greater than the realisation. There are probably a number of reasons for this; some are to do with resourcing but perhaps the most important one is to do with teacher culture. Unlike practical work, which is widely felt to be a core part of science, no similar status is attached to the use of digital technologies, beyond the long-standing use of electronic meters in fieldwork and the more recent use of internet search engines and *YouTube* clips.

A helpful, teacher-focused report on digital technologies and science education was authored by Bolstad and Buntting (2013: 17). They point out that there are many ways in which science learning can be enhanced by digital technologies. For example:

- *3-D animations and simulations can help make abstract concepts more visible.*
- *Apps can allow the easy manipulation of variables and formulae.*
- *Digital probes and motion sensors can collect accurate data systematically.*
- *Virtual labs or field trips give more ready access to laboratory or industry processes.*
- *Virtual networking enables students to connect and collaborate with each other and others, including scientists.*
- *Up-to-date scientific understanding can be accessed and shared.*
- *Data can be accessed or published online, collated, interrogated and interpreted.* (Bolstad and Buntting, 2013: 17)

Bolstad and Buntting go on to suggest some more radical possibilities. For example, digital technologies could help usher in an 'open curriculum':

> *a curriculum that constantly evolves through the input of many different people: teachers, subject experts, learners and people with the expertise, time and interest to contribute their knowledge and support to help learners engage with the changing dynamics of science in the world.* (Bolstad and Buntting, 2013: 25)

As perhaps is the case with changes to how practical work is undertaken, what is needed for new technologies to be used to best effect in science education is a change in culture. This is easier said than done but is possible. Organisations such as the Primary Science Teaching Trust (https://pstt.org.uk), the National STEM Learning Centre (www.stem.org.uk), the Association for Science Education (www.ase.org.uk) and the other professional organisations for science teachers can all play a part.

Question 9: What is the best way of assessing learning in science?

Everyone agrees that assessment plays a central role in successful teaching and learning. A standard classification identifies three purposes of assessment:

- diagnostic assessment – in which the particular areas of existing knowledge and any misconceptions of individuals are identified;
- formative assessment – in which the information gained through diagnostic assessment is used to provide feedback to learners to help them to learn effectively;
- summative assessment – in which attainment, whether knowledge and understanding, skills or (less often) dispositions, is measured in a way that allows it to be reported to the learner and others.

Of these three, it is diagnostic assessment that generally receives the least attention in science education. The Best Evidence Science Teaching (BEST) Project (www.york.ac.uk/education/research/uyseg/research-projects/bestevidencescienceteaching/) at the University of York Science Education Group (UYSEG) is currently developing materials for this purpose with funding from the Salters' Institute and these materials will be made freely available.

Some of the most exciting work in assessment in school science is currently being undertaken in primary schools, with the Teacher Assessment in Primary Science (TAPS) project (Earle *et al*., 2017) building on earlier work led by Wynne Harlen (Harlen *et al*., 2012). At secondary level, there are questions about the consequences of the new summative assessment of practical work at GCSE and A-level that time will answer.

Question 10: How can we ensure that effective piloting is undertaken for new initiatives in science education?

The tenth and final recommendation of *Beyond 2000* was:

> *A formal procedure should be established whereby innovative approaches in science education are trialled on a restricted scale in a representative range of schools for a fixed period. Such innovations are then evaluated and the outcomes used to inform subsequent changes at national level. No significant changes should be made to the National Curriculum or its assessment unless they have been previously piloted in this way.* (Millar and Osborne, 1998: 30)

Although others, including the Royal Society, have similarly called for careful piloting, it cannot be said that such recommendations have had much effect. Yet, that does not mean that we should stop arguing for them. The discipline of science is all about rigorously testing ideas and we should expect politicians and others to seek robust evidence before policies are implemented nationally. Furthermore, with the advent of the Education Endowment Fund (educationendowmentfoundation.org.uk) it is now easier to envisage a way in which such initiatives might be trialled.

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Michael J. Reiss is Professor of Science Education at UCL Institute of Education, University College London. At the time of writing, he was Master of The Salters' Company. Email: m.reiss@ucl.ac.uk