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The role and relevance of science in addressing global concerns

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The role and relevance of science in addressing global concerns

Berry Billingsley

The theme within this edition of *School Science Review* is 'The role and relevance of science in addressing global concerns'. The duration of the COVID-19 pandemic and the extent of its impacts on society, education and individual lives continue to emerge, and several articles in this theme consider the short- and longer-term consequences of those impacts. With the group I lead at the Epistemic Insight Initiative, we consider a range of perspectives on practical work to argue that, despite the challenges, it remains an essential aspect of science education. The article describes a free scheme for children in years 4–7 (ages 8–12) that is designed to promote scientific enquiry. 'Essential experiences in science' includes bright, friendly investigation cards that can be easily moved between home and school for homework or in the event of a local lockdown (Figure 1).

Fostering sophisticated epistemology of science among students has been a longstanding and cherished goal of science education. Despite decades of research, interventions and educational reform, teachers and curriculum planners continue to accept that the challenge of how to improve student perceptions of the nature of science and scientific inquiry remains. COVID-19 has been heralded as creating unprecedented times. Could it also have an unprecedented consequence for how science is presented and understood in school? Seeing science at work in the context of addressing real-world problems reminds us that the nature of truth in science is not absolute. In his article, John Wood reminds us of a quotation by the historian Edward Gibbon that the laws of probability are true in general, but fallacious in the particular (Bonnard, 1969). We can use scientific methods and mathematical modelling to discern patterns and probabilities in nature. We can write laws and computer algorithms to explain and predict patterns that emerge. But although these are useful and important descriptions of nature in general, they can create injustice and unhappiness if they are applied to individuals to make decisions. A contemporary example concerns the now aborted use of algorithms to regulate students' A-level and GCSE exam results in England, Wales and Northern Ireland. The incident is likely to prompt discussions in staffrooms and classrooms for some time. It is a chance to critique the strengths and limitations of technology and highight that there is no replacement today for human insight. There is no machine today that can walk in our shoes or experience what a student will feel when opening the envelope on results day (Figure 2). John Wood makes a case that scientific enquiry has to be combined with epistemic insight to make the possibility of tackling many of the grand challenges facing society a reality. He also describes his relationship with the European Commission on Open Science and Open Innovation. The Open Science movement seeks

Figure 1 These and other investigation cards can be taken home in the event of a local lockdown to support children's continued access to 'essential experiences in science'

Figure 2 A decision to use an algorithm to moderate students' marks is likely to be a talking point for some time

to tackle global challenges by sharing information across cultures and disciplines. John explains that the nature of Open Science is focused on the fact that knowledge can be shared via the internet, and it is how we use that knowledge that is important.

Continuing our review of ways to understand science, Sibel Erduran discusses media reporting of science during the pandemic and gives some practical ideas about how teachers can unpack information about science presented in the media. Her article unpacks the issue of framing of science in schools by asking, '*how do scientists do science?*' and '*how does reasoning in science compare with reasoning in other school subjects?*' As Sibel explains, these questions can potentially help us to identify similarities and synergies across school subjects as well as features that differentiate science from other ways of knowing.

Global concerns, including the COVID-19 pandemic, call for expertise across a wide range of disciplines. The Epistemic Insight Initiative seeks to broaden students' appreciation of the distinctive role of science and its similarities and differences with other disciplines and ways of knowing. In his article, Stephen Thompson describes the work and interests of Professor Sir Colin Humphreys, a materials scientist who seeks to advance the frontiers of knowledge in engineering and in the humanities. This article proposes that Sir Colin Humphreys would make a good case study for teachers and students to consider how a research scientist can have interests that bridge the cultural divide between science and religion.

Michael Reiss invites us to consider a contentious and challenging question for science education. He asks, 'Should we teach about the genetics of intelligence?' Michael explains that our genes are central to who we are and how we come across to others. As he notes, the links between genetics and intelligence are likely to be of interest to students and of value to society. Genetics explains how the theory of evolution through natural selection works and it is central to such applied topics as plant breeding and biotechnology. Michael goes on to make three claims, which are that '*education needs to stop ignoring the possible role of genetic inheritance in school performance*', that '*genetic inheritance can play a significant role in how well children do in schools*' and that '*this does not mean that children's school performance is predetermined, that is, fixed in advance*'.

If secondary school teachers are to work with more topics that bridge disciplines, they will probably find it useful to collaborate with colleagues in other curriculum areas. In the article I share with Robert Campbell and Matthew Dell, we reflect on an intervention that brought together trainee science and RE teachers. As the authors explain, there are many topics that lend themselves to a cross-disciplinary exploration and thus a collaborative approach. One such example is the '*nature of families, including: the role of parents and children*' (AQA, 2017: 21). The UK has recently changed its position on family law and what the legal grounds are for parents accessing genetic selection technology. In the intervention, trainees considered two case studies that prompt an examination of the scientific and ethical perspectives of using this technology to create a child who is designed to save the life of an older poorly sibling.

Finley Lawson, Megan Hunt, Daniel Goodwin and Stefan Colley extend our exploration of the benefits and outcomes of providing students with opportunities to examine science in wider contexts. Their intervention and research were focused on teenagers taking part in an informal learning activity. Their article explains the activities that students explored and is called, 'Inspiring Minds: how big questions can build students' epistemic insight and improve attitudes towards STEM'.

Within an uncertain environment, young people who are already experiencing uncertainty about how best to make successful transitions between school, university and beyond, may feel an exacerbated sense of anxiety. It becomes particularly important to ensure that students can access advice and accurate information about science-related careers. The last article, by Keith Taber and colleagues, provides some useful background to this issue. It reports an interview study that asked students to talk about the nature of scientific knowledge in the context of considering a selection of science-related careers. Students' comments revealed a range of goals that they associate with careers and the role that science plays. These included understanding the world and our place within it and using science to engineer changes.

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Science at school: a sliding doors moment in the story of school education

Berry Billingsley, Nicola Robinson, Robert Campbell and Stephen Thompson

Abstract What is the future for school science and in particular for practical work? This article explores the question from four perspectives and seeks solutions for different age groups in the UK and beyond.

The COVID-19 pandemic is incentivising teachers and many others to question what school is primarily for, and what young people need, should and want to be studying. There are further questions about which lessons can be online and which can be delayed until later in the year. For the autumn term at least, it cannot and will not be 'same old, same old' with a few tucks and changes. Indeed, this academic year has the potential to be a 'sliding doors' moment for school education and for science at school in particular.

One of the pressures that students and teachers face is implementing virus-prevention measures, but, even so, and if ways to work safely can be found, there are many reasons why prioritising scientific enquiry, including practical work, will benefit schools, families and students.

Several months of lockdown transformed most, if not all, children's experiences of school. During lockdown most teachers tried to adapt to the opportunities and necessity of distance learning, and research has indicated that approaches have varied widely, along with student engagement (Pennington, 2020). Children returning to school will be struggling to get back into the rhythm of working with direction from a teacher after very different experiences of school work over the months.

The Centre for Learning and Life Chances in Knowledge Economies and Societies (LLAKES) working paper (Green, 2020) indicates that around one fifth of school children have not engaged in formal education since lockdown, thus amplifying pre-existing inequalities in children's education (Andrew *et al.*, 2020). Many of these children will need a boost to their academic self-concept – 'why do I need to be in school at all?' Practical science was significantly reduced and became an impossibility for most children during lockdown (Canovan and Fallon, 2020). There's a basis for saying that without a change of course, scientific enquiry will continue to be reduced or missing for most children when school restarts. As we head into the new term, our interactions with teachers of science and other subjects indicate that many are discussing ways to minimise activities that require a lot of paired and group work and/or using and handling equipment; some teachers have said they are delaying practical work until later in the year and some are replacing hands-on practical with online simulations. Putting practical activity first, however, would mean that children come back to experiences that feel refreshingly different from the computer- and paper-based activities that were set during lockdown.

The challenges of living with a pandemic are a motivation to find activities that can transfer between school and home, thus increasing resilience in the event of local lockdowns in line with recent guidance (DfE, 2020). This strategy is particularly appealing for children in primary school where the focus for a lot of practical science is on working with and investigating everyday materials. By establishing more effective partnerships between teachers, children and parents/carers, we can help to address the issue identified recently by the Sutton Trust (2020), that only 42% of British parents feel confident about teaching their children at home.

Essential Experiences in Science

To support teachers looking for options, we have developed a resource called 'Essential Experiences in Science' (Figure 1), which is designed for the recovery phase for children in years 4–7 (ages 8–12), with practical experiences and other activities to build familiarity with scientific methodology and vocabulary. We hope it gives schools and families the reason and motivation they need to work together on sustaining children's access to scientific enquiry during challenging times. The resource includes bright, friendly investigation cards that can be supplemented with simple equipment such as a straw or

Figure 1 There is information about 'Essential Experiences in Science' at www.epistemicinsight.com/ees

pipette, which can easily be carried home from school each day. A set of cards and the relevant materials could also go home in the event of a local lockdown. One of the aims is for teachers and parents to create language bridges between homes and school so that children hear the same words being used for science in each location. There are webinars for teachers and/or adult carers that highlight key process words like 'observe', 'predict' and 'record', and key concepts such as 'evaporation' 'surface tension' and 'the water cycle'. With activities to cover several weeks, it means children can explore and share ideas about, for example, the properties of water, and how these properties help us to explain scientific phenomena and concepts in the curriculum (Figure 2). For the first 30 schools to get in touch, we are providing take-home discovery bags for about 30 students to support four or more activities, where the bags contain the materials children need and some bonus science equipment.

'Essential Experiences in Science' is is produced as part of the Epistemic Insight Initiative and, alongside each activity, there are explanations about how the session will develop epistemic insight and understanding of science as a discipline that asks and investigates questions about the natural world. Students can then compare science as a way of knowing, with how they enquire in other disciplines. Please get in touch if you would like more details of this free scheme, the accompanying investigation cards or the Epistemic Insight Curriculum Framework (Figure 3).

Older students in secondary school

Turning next to the challenges and opportunities to engage and teach students aged 14 and above, most people, and this includes most teenagers, want to make the world a better place. The COVID-19 pandemic has thrust science into the spotlight: most children

Figure 2 Examples of the 'Essential Experiences in Science' investigation cards

Figure 3 The Epistemic Insight Curriculum Framework

will have increased their awareness and knowledge of viruses, antibodies, vaccines and pandemics. Many in this age group will also have noticed that science has been promoted to the public as a discipline that guides and informs national policy. Some will have also seen that the relationship between science and policy has shifted over time, at least in the way that it is reported by the media. For the first few months of the pandemic, in the UK and elsewhere, government ministers repeatedly said that their decisions to lockdown countries, businesses, schools, restaurants and family life were 'guided by the science', with the singular 'science' used to justify such decisions (Honigsbaum, 2020). This probably helped to galvanise and persuade the public to make huge and significant changes but it also seems likely that it fostered or at least reinforced some misperceptions about science. 'Working scientifically' is a key strand that runs throughout the National Curriculum in England for science, and specifically understanding of the nature, processes, and methods of science for each year group (DfE, 2013). To understand the relevance, power and limitations of science in helping politicians and others to make decisions that affect our lives, students need to first appreciate that 'the' scientific advice comprises advice from specialists in a range of science and science-related disciplines, including the natural and behavioural sciences. Students also need to be aware that no area of expert knowledge (not even science!) provides a 'one-stop shop' solution to a complex, multifaceted real-world problem like how best to respond to COVID-19.

Decisions about reopening schools, shielding the most vulnerable in society and guidance on public use of face masks are made after consulting with scholars in a range of relevant disciplines. Each of these disciplines has its own preferred questions, methods and norms of thought (Billingsley *et al.*, 2018). Consider, for example, the question of whether to implement social distancing rules of 2 metres or 1 metre in shops. If 1 m becomes the standard for social distancing in shops and similar spaces, some scientists have projected that it could produce 2–10 times the infection rate; at the same time, Kate Nicholls, chief executive of the industry body UK Hospitality, says that with a 2 m rule, outlets would only be able to make about 30% of normal revenues, whereas 1 m would increase that to 60–75% (Eardley, 2020). As the Deputy Chief Medical Officer for the UK, Jonathan Van-Tam, put it during a press conference, '*decisions are a combination of "science, politics and practicality"*' (Neilan, 2020) (Figure 4).

Figure 4 Scholars in different disciplines can offer different perspectives on the implications of social distancing at 1 metre or 2 metres

Going online

Next, we turn to our fourth point to consider when deciding the future of practical science, which is: Why make the effort to provide hands-on practical if we can instead cover the essentials online? Because of the global COVID-19 pandemic, most schools in the UK have offered significantly reduced face-to-face teaching in recent months. As teachers sought to adapt their teaching, there has been an upsurge in the use of online simulations as teaching tools. This transition has been taking place internationally. In a series of online workshops organised by the OECD to consider how education can respond to the pandemic, it was remarkable to see that similar challenges have so far been met with similar attempts at solutions. A 15-year-old student, Carina, in Finland, explained her experiences of learning science online: '*It's not the same thing as being in the lab. We were supposed to be building circuits in physics but you're not actually building them, you're just using online tools to see how they work.*' (OECD, 2020).

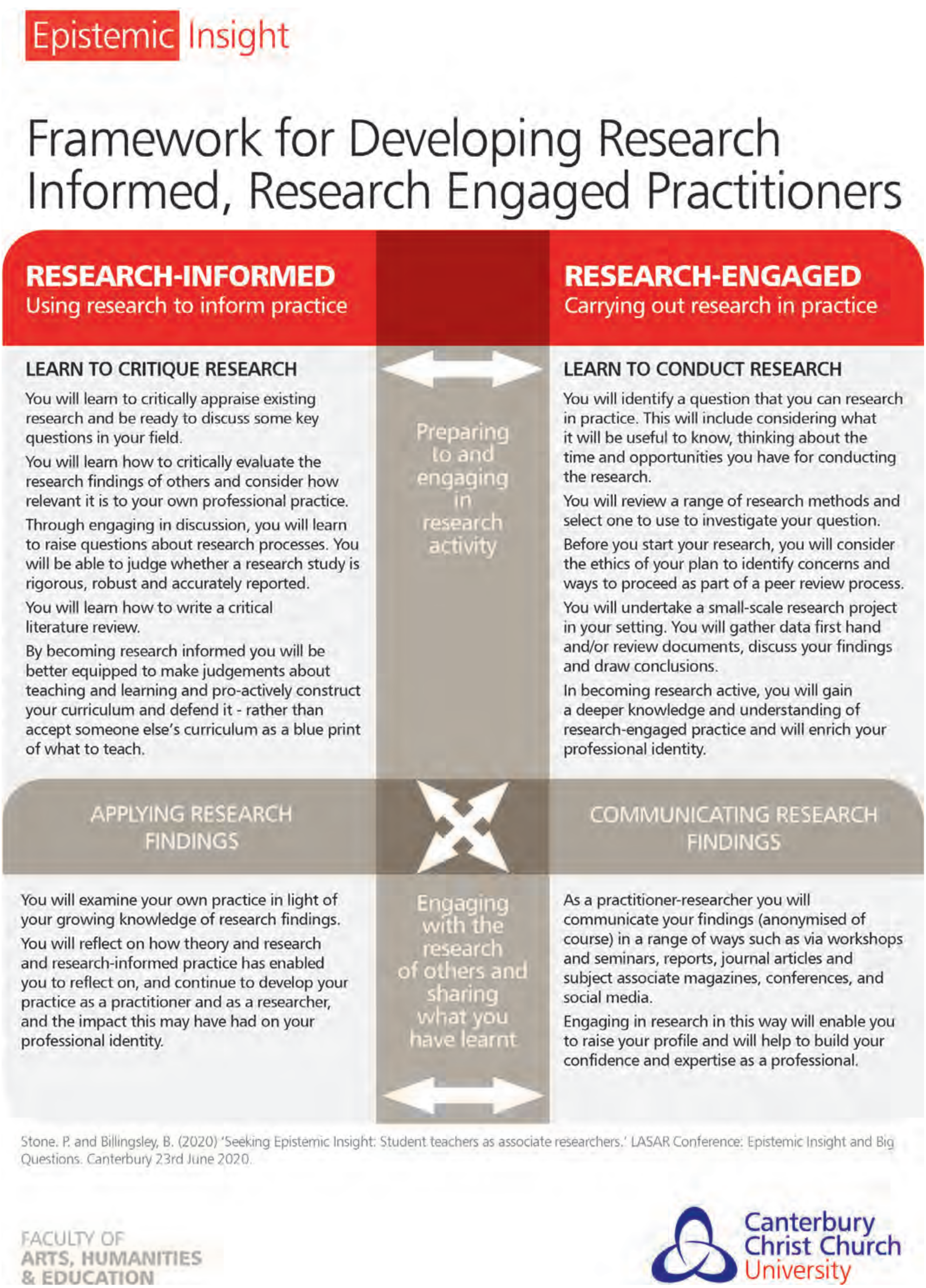
As teachers of science continue to adapt their teaching to meet the demands of the COVID-19 global pandemic, we have decisions to make about how to involve school classrooms and laboratories. Teachers have the opportunity to combine their improved familiarity with a variety of online resources with in-school learning. Conducting scientific enquiries virtually can offer an opportunity for students to raise their own questions free from the safety concerns of a school laboratory. Teachers, however, will need to reflect upon how their teaching ensures progression in all the distinct 'working scientifically' skills (Holman, 2017). For example, helping students to recognise hazards and take actions to reduce risks are important components of science education and components in any potential solution. Teaching students to consider health and safety as part of practical activities is not new, but the scale of the challenge in science teaching has reached a new level, certainly in the short term. If the risks are reduced sufficiently, students are able to go ahead with carefully selected hands-on practical activities. This facilitates courses that emphasise a broader range of enquiry skills and more explicit, exciting and relevant contexts for investigations, where students set up new lines of enquiry for themselves and evaluate the results they achieve. Working with simulations can overcome the potential challenges of faulty equipment or errors in setting up the experiment. However, it is only by comparing the results achieved in an online simulation with in-class experiments that students come to appreciate how various errors may arise, and what steps are possible to correct these. The ability to analyse secondary data in terms of validity, precision, accuracy and reliability must surely be rooted in first-hand experience of observation and data collection, because science is a study of the real world, not merely an exercise in received theory.

A position paper by the OECD (2018: 2) argues that '*the future is uncertain and we cannot predict it; but we need to be open and ready for it*'. An effective education equips students with opportunities to discover for themselves some of the complexities of advancing the frontiers of knowledge. Experiencing a range of single-, cross- and multidisciplinary enquiries while making use of first-hand and secondary sources of data will help students to become more astute as the future producers of new knowledge and as wiser knowledge consumers. COVID-19 has been described as the greatest challenge for the world since the Second World War (BBC, 2020). At the same time, it is raising the profile of scientific research and vanquishing longstanding habits and regulations in systems like education, which opens the way for progress, invention and innovation (TES, 2020).

The Epistemic Insight Curriculum Framework has been used in schools and initial teacher education through 30 action research projects by teachers, tutors, student teachers and researchers. These projects aim to find ways to improve students' understanding in practice of the nature of knowledge – including, and in particular, students' understanding of the power and limitations of science in real-world contexts and multidisciplinary arenas. The research is timely in the current situation. Most teachers (11 out of 13) who participated in a survey answered 'yes' to the question, '*Do you think you will be using the Coronavirus Pandemic as a tool in the future to engage students e.g. when teaching about microorganisms, vaccines, immunity (other)?*' (Robinson, 2020). One teacher added the comment: '*This is undoubtedly one of the biggest global challenges the world has faced. It will go down in history as such. I cannot imagine any half decent education system not covering it.*' (Robinson, 2020: 5).

Many of the interventions are based around the core theories developed in our earlier work, such as that in secondary schools entrenched compartmentalisation – the various ways in which pedagogy is habitually narrowly focused on content within specific disciplines – precludes the development of an awareness of the relationship between disciplines and the relationship of disciplinary knowledge to real-world contexts (Billingsley, Nassaji and Abedin, 2017). This prior work pointed to connections between these issues and a persistent lack of diversity in STEM.

Our future work will continue to seek ways to increase the number and diversity of students who want to study science. The strategies we are testing include providing students with opportunities to examine the role and relevance of science when deciding how to respond to global concerns. For teachers and teacher



Epistemic Insight

Framework for Developing Research Informed, Research Engaged Practitioners

RESEARCH-INFORMED
Using research to inform practice

RESEARCH-ENGAGED
Carrying out research in practice

LEARN TO CRITIQUE RESEARCH

You will learn to critically appraise existing research and be ready to discuss some key questions in your field.

You will learn how to critically evaluate the research findings of others and consider how relevant it is to your own professional practice.

Through engaging in discussion, you will learn to raise questions about research processes. You will be able to judge whether a research study is rigorous, robust and accurately reported.

You will learn how to write a critical literature review.

By becoming research informed you will be better equipped to make judgements about teaching and learning and pro-actively construct your curriculum and defend it - rather than accept someone else's curriculum as a blue print of what to teach.

Preparing to and engaging in research activity

LEARN TO CONDUCT RESEARCH

You will identify a question that you can research in practice. This will include considering what it will be useful to know, thinking about the time and opportunities you have for conducting the research.

You will review a range of research methods and select one to use to investigate your question.

Before you start your research, you will consider the ethics of your plan to identify concerns and ways to proceed as part of a peer review process.

You will undertake a small-scale research project in your setting. You will gather data first hand and/or review documents, discuss your findings and draw conclusions.

In becoming research active, you will gain a deeper knowledge and understanding of research-engaged practice and will enrich your professional identity.

APPLYING RESEARCH FINDINGS

COMMUNICATING RESEARCH FINDINGS

You will examine your own practice in light of your growing knowledge of research findings.

You will reflect on how theory and research and research-informed practice has enabled you to reflect on, and continue to develop your practice as a practitioner and as a researcher, and the impact this may have had on your professional identity.

Engaging with the research of others and sharing what you have learnt

As a practitioner-researcher you will communicate your findings (anonymised of course) in a range of ways such as via workshops and seminars, reports, journal articles and subject associate magazines, conferences, and social media.

Engaging in research in this way will enable you to raise your profile and will help to build your confidence and expertise as a professional.

Stone. P. and Billingsley, B. (2020) 'Seeking Epistemic Insight: Student teachers as associate researchers.' LASAR Conference: Epistemic Insight and Big Questions. Canterbury 23rd June 2020.

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Figure 5 This guide is designed to help practitioners to develop as researchers; it is one of the resources freely available as part of the Epistemic Insight Initiative educators interested in knowing more, there are details on the website www.epistemicinsight.com. These include a guide for supporting research-engaged teaching (Stone and Billingsley, 2020) (Figure 5).

To conclude

The duration of COVID-19 management measures in education cannot yet be predicted, but it remains the case that practical inquiry is a cornerstone of the science-based professions, and so it must be a cornerstone of science education and a necessary component of an effective education. Practical work is not only an insight into how scientists work but also an intellectual basis from which to contemplate the proper role of science when we tackle questions that concern individuals and society. As such, it is an important way to build disciplinary knowledge about science (Ofsted, 2019). The silver lining from COVID-19 is that teachers now have an opportunity to combine the strengths of online simulations with the motivating and engaging nature of face-to-face practical and the relevance of real-world contexts to create a genuinely blended, multidisciplinary and future-seeking approach to the curriculum.

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The Open Science movement

John Wood

Abstract This article looks at how the nature of truth in science is not absolute and in accepting the idea that certain 'laws' are sufficiently true we can unlock the rigidity of discipline-based scientific thinking to make the possibility of tackling many of the grand challenges facing society a reality. The nature of Open Science is focused on the fact that knowledge is freely available via the internet and it is how we use that knowledge that is important. Two examples are chosen to demonstrate how this is now being used by school and university students.

In a talk at the Museum of London, UK, the neuroscientist Professor Peter Fletcher (2019: 4) said:

> *Our apprehension of reality depends on a process of balance or negotiation between the signals that we receive and the predictions that we make based on experience. These predictions are crucial to making good perceptual inferences but this comes at a cost – the price of being useful is that we may not be absolutely accurate.*

How true – and here is an example of where, in my own experimental work, the perils of expectation caught me out.

I have been an experimentalist all my scientific life. I used to call myself an atomic anarchist since I liked to force atoms to adopt positions that were well away from equilibrium using a variety of techniques. I observed the resulting structures, employing the most powerful ion, photon and electron sources available as well as various spectrographic and other techniques to interrogate their properties. One day I was brought up short, having written a paper on a certain silver-based compound where I had seen a certain defect, only to find another colleague had looked at my samples and seen something completely different. We had both mentally filtered what we saw, reflecting our own backgrounds and interests. It was a salutary lesson. This is exactly what I had done. I had seen what I expected to see and filtered out other evidence. I needed to see the wider picture.

There is no doubt that scientists sometimes hold on to their theories tenaciously and pour scorn on other ideas. So how do we determine whether something is true in science? Is there such a thing as absolute truth in science? Much depends on where you are looking from or your starting point.

The historian Edward Gibbon has said of the laws of probability, that, while they are true in general, they are fallacious in the particular (Bonnard, 1969). We know this to be true in everyday life. The behaviour of the crowd is different from that of the individual, and in economics the actions of the individual are often so different from that of society. The same is true of atoms. Those atoms on a surface act differently to those in the bulk. This is the basis of so much surface chemistry and nanotechnology. This is easily demonstrated to students by various effects of surface tension, for example capillary rise or a film of water holding glass plates together.

So, can we trust science and scientists and especially what they say in public? An Ipsos MORI (2019) poll showed that the most trusted profession was nursing at 95% with scientists coming in at 84%, just below teachers at 89%. Not surprisingly, politicians scored just 14%! However, scientists themselves can be dubious about the legitimacy of their subject.

On time: new and so often perplexing

The work we do in science is and should be perplexing. The theoretical physicist Carlo Rovelli writes in his book *The Order of Time* (Rovelli, 2017): '*Nothing is valid always and everywhere. Sooner or later we always come across something that is new.*' In the book, Rovelli looks at the nature of time, pointing out that time goes faster at the top of a building than at ground level (a

scientific prediction by Einstein that has since been verified), and how atomic clocks corrected for time distortion are needed for the GPS system to work on your smartphone. He takes us down to scales beyond our imagination, to the Planck time, which is the time a photon takes to travel the across the Planck length of a hundred millionth of a trillionth of a trillionth of a trillionth of a second. After that, time has no meaning. At this point, Rovelli writes, '*The time of physics is, ultimately, the expression of ignorance of the world. Time is ignorance!*'

I learnt to look at time differently when I was once in South Africa waiting for a taxi. It was late and I was getting impatient when my African colleague commented with an African saying: '*Westerners have watches, Africans have time!*' As scientists, we think that the forward movement of time, defined by an increase in entropy, is constant. It isn't – once you dig below the surface.

Is truth in science an illusion?

Where does this leave us? Are we deluding ourselves and is our conception of truth in science an illusion? How can we help school students to appreciate that what they are taught is rarely, if ever, the end of the story? One big difficulty for many university science students and students in secondary school, is that what they have understood as 'scientific laws' are not absolutes but approximations to the truth. When my children were taking GCSEs, we had to have an agreement that there was 'school science', which was dictated by questions with answers that were deemed correct, and 'real science' where there were many uncertainties.

We should be careful not to throw out the baby with the bathwater. Take the example of Newton's (so called) laws. We know they break down at small scales and the theory of quantum mechanics takes over, but even that breaks down it seems when we get to absurdly small sizes such as the Planck length. For most of us in our everyday lives, Newton's approximations are more than sufficient and we can use them to make the calculations to take people to the Moon and back. I want to make a case for saying that these are not the absolute truth but they are 'sufficiently true' as long as we teach the limits of their applicability and ensure students are open to further possibilities.

There are big moves in science going on at the moment that change the very way science is being done internationally. It was only just over a hundred and fifty years ago that the concept of individual scientific disciplines began to develop. Since then, the word 'science' in English has become more restrictive and also abused. We constantly hear on the radio or read in the newspapers that 'science says' without any justification about the context in which this statement is made or any background that might indicate there are other factors that need to be taken into account. In Germany, for instance, the English word 'science' is often translated as '*wissenschaft*', which is a much broader term and includes all forms of scholarship including humanities. Reflecting on this wider definition helps to give 'science' its place in discussions.

Open Science

We need to develop this holistic approach to help us to tackle the enormous challenges facing society. A holistic approach means that scientific data are viewed through many lenses and scrutinised and turned into useful ideas by those looking at them from many different perspectives.

The internet and public interest in science can be a key part of how this happens in practice. The term that has come to define this approach is called 'Open Science', hence the title of this article – 'The Open Science movement'.

The term Open Science can be loosely defined as representing a new approach to the scientific process based on cooperative work and new ways of diffusing knowledge by using digital technologies and new collaborative tools.

The Open Science movement has now been adopted by policymakers and funders around the world and now needs to cascade down to schools so that students are prepared for the new ecosystem that is developing. The internet plus the ability to freely interrogate data from a vast range and number of sources needs to be harnessed at every level in society.

Open Science: looking critically at data

Teaching students how to look critically at data is just one specific requirement. International organisations such as the Committee on Data of the International Science Council (CODATA; https://codata.org) and GO FAIR (www.go-fair.org) are developing best practices and training tools and it is widely accepted that data literacy needs to be taught right from the beginning and not as a catch-up later. One of the most exciting areas of Open Science is that of so called 'Citizen science'. Hundreds of projects have sprung up in the past decade whereby citizens can take part in scientific projects (using the wider definition of *wissenschaft*), including in social history, biodiversity, climate change and studies on Shakespeare. The website zooinverse.org allows easy access to many of these projects. Perhaps the best known is 'Galaxy Zoo', whereby over half the galaxies found by the Hubble Space Telescope have been identified by people who are not trained astronomers.

Open Science: robotics

It is not possible to outline all that is happening around the Open Science initiative in this short article, but here are two examples of how this approach is developing. At the John Warner School in Hoddesdon, Hertfordshire, there is a robotics club where secondary school students of various ages take part in a competition against others. Each team divides up the work packages so that one person looks after communications, one writes the technical specification, one works out the programs, one works out tactics and they all take part in the build. This brings together literacy, design, logic, digital, mechanical, manipulative and debating skills among others, so that a winning team emerges by sharing disciplines. This is a modest example, but on visiting the school one cannot but be impressed by the students' enthusiasm and commitment. The teacher who runs this programme is an inspiration and is now working with local primary schools to develop the same approach. The question is how can this approach be fitted into a crowded curriculum?

Open Science: IdeaSquare, CERN

A more ambitious programme called IdeaSquare is being led at CERN in Geneva (https://ideasquare.cern/ideasquare-landing-page). Here, a disused warehouse has been refurbished to be a place where students from all over the world come with their teachers and mix together culturally and between disciplines. The approach is called 'challenge-based innovation'. Initially, a small challenge to use cardboard to build a robot that can display three human emotions allows the teams to gel and get to know each other. This is followed by the teams being given a bigger challenge, normally one connected with the United Nations' strategic development goals. After spending a few more days at CERN they return to their universities and disciplines and try to find out what they need to learn to attempt to make an impact on the challenge. During this period, they need to learn about financial, social, scientific and technological aspects so that they can make a presentation, on their return to CERN at the end of the project, to a group of people from various backgrounds who vote on the best presentation and solution. This approach has been adopted by a course for masters' students, and there are pilot projects for school students being undertaken using similar techniques. One very exciting development has involved students from the Royal College of Art (RCA) in London. An initial group of 20 students was involved and this has now mushroomed to over 400 students signing up for what is a three-month project ending up with presentations to the media at the RCA. CERN provides the mentors, including myself. Almost none of the students are scientists but they start to tackle problems around dementia, microplastics in water, food security, and so on.

On arrival at the IdeaSquare building, students read the following:

> *Welcome to IdeaSquare, a place where scientists and society meet to push the boundaries of knowledge and to share and explore new ways to reach societal impact through research and technology. A space designed for collaboration through curiosity, creativity and science. A place where people have a licence to dream.* (IdeaSquare, 2019)

Conclusion

The task for education is always to try to equip those at school now with the aptitudes and attitudes that they will need in their lives now and in the future, as professionals and citizens. For the generation of scientists who are still in school now, working in an internet-rich environment is something they probably take for granted, so it seems reasonable to build this into the practices and content of learning. It is acknowledged that embedding a more holistic approach from an early stage is challenging to schools and teachers in particular. It is one of the aims of the Epistemic Insight Initiative to provide frameworks for use in schools to help teachers with how this can be done and, importantly, to convince policymakers of the value of this approach for the future of society. For details of the recent policy advice on Open Science see https://ec.europa.eu/research/openscience/index.cfm.

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Reframing science education in light of the COVID-19 pandemic

Sibel Erduran

Abstract The COVID-19 pandemic demonstrates how understanding science in context is not a luxury but a necessity in our times. In order to make sense of a complex issue such as a pandemic, pupils need to understand not only how scientists do science but also how science relates to other school subjects. By drawing on findings from funded research projects based at the University of Oxford, the article provides concrete strategies for meaningful engagement in practical science and cross-subject discussions.

The emergence of the COVID-19 pandemic on the global stage has put science and scientists on public display. The pandemic has placed demands on the public to make sense of scientific phenomena in social context almost on a daily basis. Politicians are referring to 'the science' in their daily briefings about the virus, and the public is expected to make sense of some fairly complex information.

In a recent editorial of the journal *Science & Education*, I called for caution in how science is covered in the public domain and offered some thoughts on what science education can aim to do in order to avoid confusion and misinformation about science (Erduran, 2020). In this article I reflect on some of the ideas in the editorial and extend the discussion to what we have learned from research projects on how to reframe science education in the light of the COVID-19 pandemic.

Learning science in context

My first comment is that the information that politicians discuss in their briefings is relevant not only to science (e.g. virus, models) and mathematics (e.g. graphs, probability) but also to social sciences such as economics (e.g. risk, cost–benefit) and sociology (e.g. ethnicity). Indeed, the COVID-19 pandemic is an example that demonstrates how understanding science in context is not a luxury but a necessity in our times. If the goal of science education is scientific literacy, science lessons in schools can no longer afford to present science in isolation, not linking it to other school subjects. Comparing the COVID-19 pandemic to past pandemics (history), dealing with the grief of losing loved ones and seeking meaning in the tragedy (religious education), using technology for production of personal protective equipment (PPE), work, learning and family (computer and information technology) are some illustrations of science as situated in a complex array of contemporary issues.

Secondly, we are not starting from scratch. Learning science in context can facilitate understanding of how ways of knowing in science compare to other ways of knowing, and how different ways of knowing can be reconciled. Existing initiatives such as the epistemic insight approach (Billingsley and Ramos Arias, 2017) have long warned of the danger of presenting school subjects in silos, and developed practical strategies to support teaching and learning. The COVID-19 pandemic is now reinforcing the need to reconsider how science is framed in schools, as a subject on its own but also in relation to other subjects.

Developing practical strategies

To indicate what this might mean in practice, I will unpack the issue of framing of science in schools by raising two broad questions:

- How do scientists do science?
- How does reasoning in science compare with reasoning in other school subjects?

Together, these questions may potentially help us to identify synergies across school subjects, as well as features that differentiate science from other ways of knowing. My colleagues and I are currently engaged in two funded projects that are addressing these fundamental questions. Project Calibrate, funded jointly by the Wellcome Trust, Gatsby Foundation and Royal Society, is investigating how summative assessments can be designed to promote effective teaching and learning of practical science. The OARS (Oxford Argumentation in Religion and Science) project, funded by the Templeton

World Charity Foundation, is exploring how collaboration between science and religious education teachers can be supported in order to infuse argumentation (or justification of claims with evidence and reasons) into their lessons. Both projects extend across three years and include teachers' professional development as a central feature in order to incorporate particular approaches to practical science and argumentation respectively. Both projects are challenging our conventional wisdom about how schools frame science and scientists' ways of knowing.

How do scientists do science?

Let me unpack the first question. How *do* scientists do science? Does school science represent what scientists do? A fairly typical depiction in school of how science is done involves the so-called 'scientific method'. The scientific method is depicted as a linear process whereby scientists ask questions, design investigations, interpret data and produce conclusions. They generate hypotheses and test them by well-designed investigations. The investigations include identifying the independent and dependent variables. The overall process is presented to the pupils in a fairly unproblematic manner. The process works and science owes its success to this systematic and rational process. Yet, what happens in many school activities is that, more often than not, the experiments do not work and the results are therefore not conclusive! Pupils are then left to wonder how trustworthy the experimental approach is and they have to rely on the word of the teacher about the validity of the expected outcomes that they did not observe themselves.

The singular projection of the scientific method as a stepwise and linear process based on experiments is simplistic and hardly a realistic representation of how scientists actually do science. Rather, scientists employ a wide array of methods, some of which include hypothesis testing, while others do not involve manipulation of variables but simply observation of phenomena or measurement of parameters (Erduran and Dagher, 2014).

Sometimes scientists do not carry out experiments at all because the questions they ask do not require experiments. Consider, for instance, how cell biologists may investigate the structure and function of haemoglobin. They would be interested in this particular protein because of its role in gaseous exchange in the body. They are interested in observing the features that facilitate binding of oxygen and carbon dioxide. They may model these processes. However, they do not design experiments and change variables to see outcomes in an experimental sense. The experimental framework would be irrelevant to their research goals. The issue of 'generalisability' that is often attributed to science also does not apply. An investigation focusing on the particular problem of gaseous exchange through haemoglobin would render generalising the outcomes to other proteins meaningless! However, the way that cell biologists are doing science is not any less scientific. In other words, doing an experiment or generalisability of results are not requirements for a process to count as scientific. Indeed, sometimes scientists can test hypotheses without conducting experiments. Astronomers, for example, test many hypotheses about planets and distant galaxies without ever manipulating any variables but rather by carrying out non-manipulative hypothesis testing. Sometimes scientists simply measure parameters that help them reach conclusions about phenomena, such as the formation of a star in the distant past. Experiments too, of course, play an important role in science, but they do not have a monopoly in scientific methods.

In a recent blog published by the British Educational Research Association, my colleagues and I gave the following examples to illustrate how the diversity of scientific methods might be applied in the COVID-19 case:

> *Consider the current investigations around* [COVID-19] *infections. Some data are collected around how the virus might be influencing a patient's breathing over a period of time. Such observation is simply based on the recording of parameters where there is no manipulation of variables in the sense of an experimental design. Likewise, sometimes these data might be subjected to hypothesis testing about correlation between incubation period and extent of lung disease, but without having been part of an experiment. This would result in some non-manipulative hypothesis testing. Eventually scientists will have carried out some randomised control trials in which a drug could be treated as a variable in interventions that also include control groups to test the placebo effect. The important point is that all these different approaches are essential to the conduct of science, and there is no one single method but rather a diversity of scientific methods.* (Erduran, Childs and Baird, 2020)

Project Calibrate

How is the diversity of scientific methods captured in school science? A place to start answering this question is through summative assessment. Despite decades of reform in the assessment of practical science in England at GCSE (up to age 16), because of their high stakes nature, these assessments tend to promote a narrow view of the scientific method, whereby pupils carry out practical work that is formulaic and more of a hoop-jumping exercise – very far from the ways in which scientists do science in addressing key challenges such as the COVID-19 pandemic. When my colleagues and I investigated the examination questions from different examination boards as part of Project Calibrate, we found that there is disproportionate emphasis on different methods (Cullinane, Erduran and Wooding, 2019). When we analysed chemistry examination questions, we observed that there were relatively more questions dedicated to non-manipulative parameter measurement than to manipulative parameter measurement. The relative distribution of marks, on the other hand, was not consistent, suggesting that more marks were dedicated to manipulative parameter measurement relative to the number of items covered in the examination questions. In other words, even though most questions did not involve manipulation of variables, those that did include manipulation of variables were awarded higher marks. This suggests that there was potentially a particular bias towards the experimental method in terms of weight in the marking.

The biasing of particular scientific methods may have the unintentional effect of curbing many pupils' enthusiasm and creativity about science. The dominance of the experimental method might communicate to the pupils that some sciences that rely on other approaches to doing science (e.g. classification) are less scientific or worthy. In the context of Project Calibrate, we have designed a series of assessments for GCSE that not only incorporate different scientific methods but also ask pupils to evaluate and contrast these different methods. Box 1 illustrates an example about mixtures. Pupils are presented with four scenarios about different investigations. They are then asked to identify hypotheses and to question whether or not an investigation can be scientific if it does not have a hypothesis. If such assessments were commonplace, presumably there would be more incentives to teach evaluation and comparison of scientific methods, given that examinations often drive what is taught in lessons. Ultimately, pupils would be provided with learning opportunities to understand that there is diversity in approaches to doing science.

How does reasoning in science compare with that in other school subjects?

I will now turn to the second question about how reasoning in science compares with reasoning in other school subjects. As I indicated earlier, the COVID-19 pandemic has made it fairly clear that understanding science devoid of context will do disservice to public understanding of science. It would be reasonable to expect that at the current time, when thousands of people are losing their lives to a deadly virus, many pupils will question why? Some pupils might indeed be losing their own family members to the deadly virus. Why do so many innocent people have to die, some being without the company of their families as they do? While in religious education (RE) lessons, children may have the opportunity to pursue such big questions, science lessons often discourage the exploration of big ideas that have philosophical undertones. Although there is typically minimal interaction between science and RE teaching, there are times when issues concerning the other subject do come up in lessons (e.g. Billingsley *et al.*, 2016) where teachers need to be in a position to address pupils' questions.

Science in schools is often presented as a collection of hard facts devoid of any values. Yet studies on the nature of science illustrate that science is not devoid of values (Mujtaba, Reiss and Stones, 2017). Science operates through a process where claims are justified with evidence and reasons, but the process is also mediated by certain social values. For example, 'commitment to evidence' is a value that scientists need to possess if they are to take evidence from investigations seriously. Other social values would include honesty and respect for colleagues. There is nothing within the objective and rational repertoire of science that would necessitate commitment to evidence. Commitment to evidence is a social value. As discouraging as school science might be in incorporating values in science lessons, even those like 'commitment to evidence' that are closely related to doing science, it is inevitable that big and often controversial questions will find their way into classroom conversations. For example, in the context of biology lessons teachers might be questioned about whether or not genes should be cloned or edited, appealing not only to scientific knowledge about genes but also to religious values about people being special creations. Some teaching and learning scenarios might require teachers and pupils to consider both scientific and religious issues together. For instance, end-of-life decisions may need to consider scientific evidence as well as religious principles about sanctity of life. However, many teachers and their pupils are not sufficiently equipped to understand how judgements are made through justification of claims with evidence, reasons and values in different subjects such as science and RE.

The OARS project

In our OARS project, we have been researching how science and RE teachers and pupils can be supported in understanding the content and process of justifying scientific and religious claims (Erduran *et al.*, 2019). The justification of claims with reasons and evidence is often referred to as 'argumentation'. Argumentation so defined does not necessarily denote conflict but rather points to how judgements are made through a process of negotiating claims and reasons. The project has been developing, implementing and evaluating a teachers' professional

Box 1 Project Calibrate assessments on evaluating a range of methods related to mixtures

Question 5 Summary

Students are investigating water samples.

Student A thought that a water sample with a pH of 7 was pure. To find the pH the student added universal indicator solution to a sample of tap water.	**Student B** investigated the boiling point of the water samples. The student measured the temperature the samples boiled at.
Student C compared seawater and bottled water. The student predicted that seawater contained more impurities than bottled water.	**Student D** tested a sample of bottled water to see which ions were dissolved in the water.

5.1 Which two students are testing a hypothesis?

Student .... and student .... [1 mark]

5.2 Write down the hypothesis that one of these students is investigating.

Student ....

Hypothesis:

....

.... [1 mark]

5.3 Name one student who did not make a hypothesis.

Is this a scientific investigation?

Circle either 'Yes' or 'No' below and then justify your answer.

Student ....

Scientific investigation? Yes / No

Justification:

....

....

.... [3 marks]

5.4 Make a prediction about the results of student **B**'s experiment with a pure water sample and with an impure water sample.

Draw a line from the type of water sample to the predicted boiling point.

Water sample	**Boiling point**
	−2 °C
Impure water	0 °C
Pure water	2 °C
	98 °C
	100 °C
	102 °C

[2 marks]

5.5 Compare the methods of student **A** and student **B**.

Which method is likely to be the most accurate in showing if a water sample is pure?

Explain why the method is more accurate.

....

....

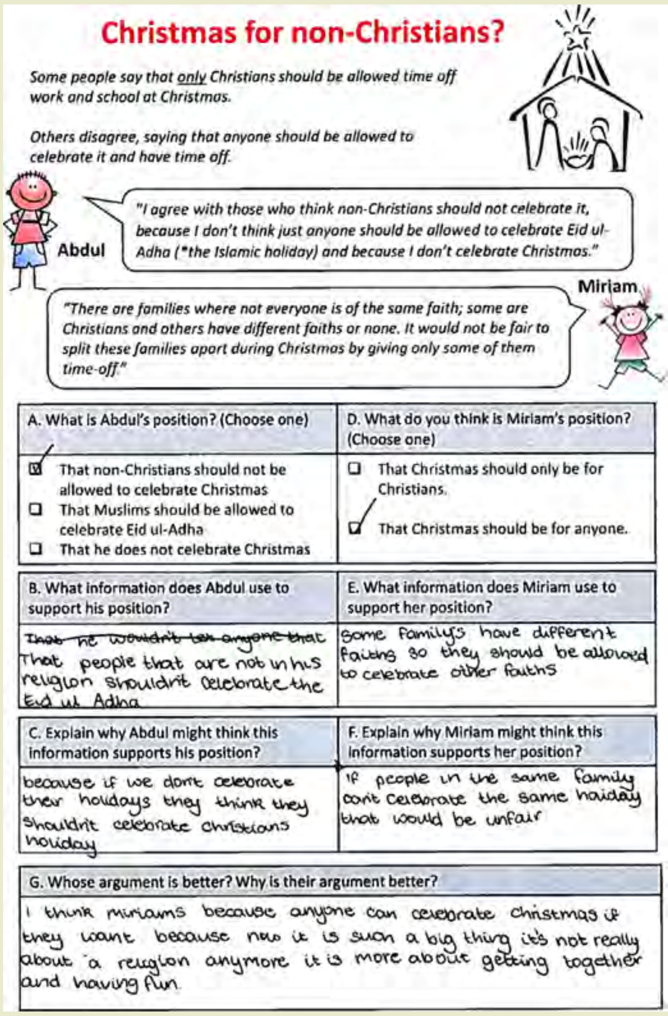
.... [3 marks]

project calibrate

DEPARTMENT OF EDUCATION   UNIVERSITY OF OXFORD development programme in order to nurture teachers' pedagogical skills in teaching argumentation in science and RE. Our particular interest is in understanding complex judgements, especially where they integrate judgements from the sciences and religions. Hence, a key component of the project is how to compare arguments from the sciences with arguments made in religious studies, drawing out implications for teaching and learning. While there appear to be many differences (e.g. fact versus value), we note that there are also commonalities (e.g. pattern of reasoning with arguments).

Hence, there is a pattern of reasoning in both science and RE where ideas are put forward with some reasons and justification for why they should be believed in. For example, Christians believe in the sanctity of life, that life is holy and belongs to God and therefore only God has the power to take life. The specific points related to these ideas are found in Romans 12:17–19: '*Do not repay anyone evil for evil. Be careful to do what is right in the eyes of everybody … Do not take revenge, my friends, but leave room for God's wrath, for it is written: 'It is mine to revenge; I will repay, says the Lord'.*' Here there is a 'claim' that only God has the power to take life. The 'reason' is that life is holy and it belongs to God. The 'justification' being offered is the idea of the sanctity of life. This pattern of claim–reason–justification can be extended to a science example. Plants require water to grow because water combines with carbon dioxide to produce oxygen and carbohydrates. Here the main claim is that plants require water to grow and the reason is that water is part of a chemical reaction in plants. The justification of the argument is that growth is about a chemical reaction. There are also examples where one particular claim might call for the inclusion of scientific ideas and religious values together. For example, a doctor might claim that it is in the interest of a patient for his or her life to be terminated. Such scenarios demand the consideration of both scientific and religious reasons and values in unison. As such, these are not only hypothetical examples, but they are also directly relevant to and prevalent in public life, particularly in light of the current pandemic. Yet, many members of the public are ill equipped to properly understand what counts as an argument and how the process of argumentation works in the sciences and religions.

Box 2 OARS project resources for writing arguments in the context of religious and science education



Christmas for non-Christians?

Some people say that only Christians should be allowed time off work and school at Christmas.

Others disagree, saying that anyone should be allowed to celebrate it and have time off.

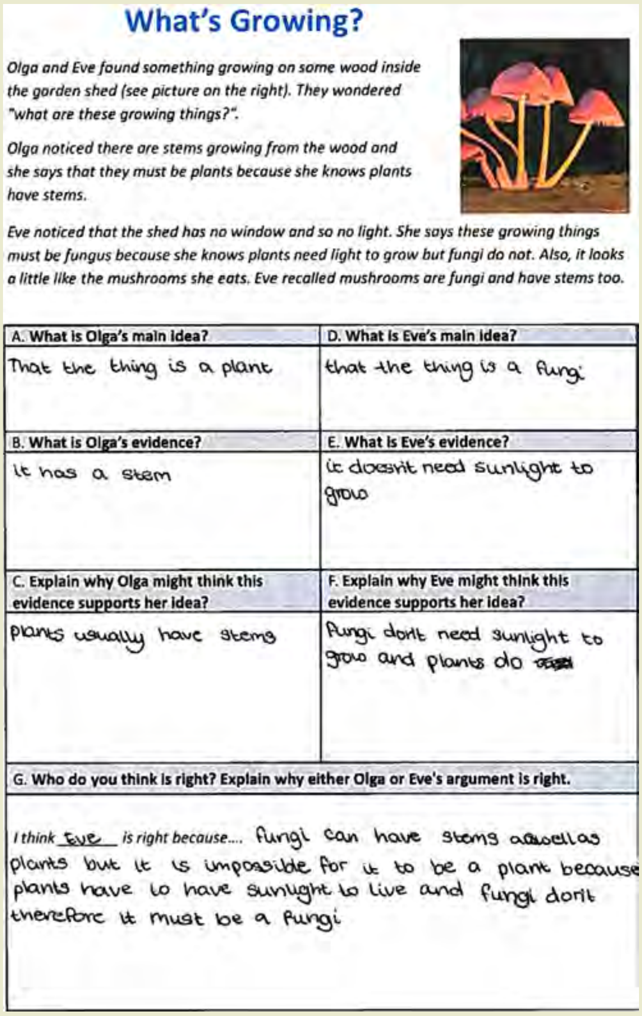
Abdul: *"I agree with those who think non-Christians should not celebrate it, because I don't think just anyone should be allowed to celebrate Eid ul-Adha (*the Islamic holiday) and because I don't celebrate Christmas."*

Miriam: *"There are families where not everyone is of the same faith; some are Christians and others have different faiths or none. It would not be fair to split these families apart during Christmas by giving only some of them time-off."*

A. What is Abdul's position? (Choose one)	D. What do you think is Miriam's position? (Choose one)
☑ That non-Christians should not be allowed to celebrate Christmas ☐ That Muslims should be allowed to celebrate Eid ul-Adha ☐ That he does not celebrate Christmas	☐ That Christmas should only be for Christians. ☑ That Christmas should be for anyone.
B. What information does Abdul use to support his position?	**E. What information does Miriam use to support her position?**
~~That he wouldn't let anyone that~~ That people that are not in his religion shouldn't celebrate the Eid ul Adha	Some familys have different faiths so they should be allowed to celebrate other faiths
C. Explain why Abdul might think this information supports his position?	**F. Explain why Miriam might think this information supports her position?**
because if we don't celebrate their holidays they think they shouldn't celebrate christians holiday	If people in the same family can't celebrate the same haliday that would be unfair

G. Whose argument is better? Why is their argument better?

I think miriams because anyone can celebrate christmas if they want because now it is such a big thing it's not really about a religion anymore it is more about getting together and having fun.



What's Growing?

Olga and Eve found something growing on some wood inside the garden shed (see picture on the right). They wondered "what are these growing things?".

Olga noticed there are stems growing from the wood and she says that they must be plants because she knows plants have stems.

Eve noticed that the shed has no window and so no light. She says these growing things must be fungus because she knows plants need light to grow but fungi do not. Also, it looks a little like the mushrooms she eats. Eve recalled mushrooms are fungi and have stems too.

A. What is Olga's main idea?	D. What is Eve's main idea?
That the thing is a plant	that the thing is a fungi
B. What is Olga's evidence?	**E. What is Eve's evidence?**
it has a stem	it doesn't need sunlight to grow
C. Explain why Olga might think this evidence supports her idea?	**F. Explain why Eve might think this evidence supports her idea?**
plants usually have stems	fungi don't need sunlight to grow and plants do

G. Who do you think is right? Explain why either Olga or Eve's argument is right.

I think Eve *is right because....* fungi can have stems aswell as plants but it is impossible for it to be a plant because plants have to have sunlight to live and fungi don't therefore it must be a fungi

Box 2 illustrates a set of activities that the OARS project has produced where the pupils are supported in their writing of arguments in science and RE contexts. In both cases, main claims are presented with some reasons and evidence, and pupils are asked to provide justifications for which claims they agree with and why. While both activities share a framework where pupils justify claims with evidence or reasons, it is worthwhile to mention that, broadly speaking, science and RE have different ways of approaching arguments. When we asked science and RE teachers to reflect on the nature of arguments in their subjects, the science teachers were quick to highlight accuracy of answers in science, whereas the RE teachers judged arguments to be tentative by nature:

> *It's important for students to realise there are different views, but also that we can arrive at answers that are worth more than simple opinions through examining and testing evidence.* (Science teacher)

> *The subjective nature of the subject [RE] means that the pupils need to assimilate a volume of information before coming to a conclusion. It also allows these conclusions to be continually tested throughout their life.* (RE teacher)

Conclusion

Collectively, the findings from Project Calibrate and the OARS project are pointing to the nuances of scientific methods and ways of reasoning in science versus other school subjects such as RE. At a time of global emergency, it is vital that pupils studying science are equipped with understanding of such nuances. The uncertainty of COVID-19 may potentially promote a sense of scepticism if pupils cannot understand how scientific methods and ways of reasoning work. The complexity of issues presented by COVID-19 in everyday life calls for rethinking about how science-in-context is framed in schools.

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A relationship with nature – through the lens of a science teacher during lockdown

Maureen Smith

Abstract Over three months of lockdown, science teacher, Maureen Smith took a camera on her daily walk by the Birmingham lakes. The images she captured included a swan incubating her eggs, litter left by human visitors and some amazing sunsets. Maureen provides a narrative alongside a selection of the photographs to discuss how they illustrate some of topics she teaches in the curriculum including human impact on the environment.

During the coronavirus (COVID-19) lockdown period, school closures and government guidelines to stay home meant that my recommended ‘one exercise walk/run per day’ could now take place in my local park. Witton Lakes park is between the Perry Common and Erdington areas of Birmingham, England, UK. As I will explain, this led to me recording in photographs what I saw over a three-month period.

It began early in lockdown when my eye was caught by the sight of a swan incubating her eggs and trying to protect them the best way she could (Figure 1). Before long, I was reaching for my smartphone to capture the scene I was watching. It was a strategic feeding approach, which had the advantage that it attracted gifts of bread, rice and other food from walkers who were about 5 metres away as they passed. Strategic, even if it meant sometimes having a clash with dogs let off their leads by their owners.

As a biology teacher, I thought then of the National Curriculum for Science in England and became excited at the idea of gathering useful resources. Here was an opportunity to capture in a photo some of the many

Figure 1 Left: A female swan tidying her nest – at a glance, there seem to be three eggs but careful inspection shows that there are six. I was told that she had eight eggs originally but only four hatched successfully. Litter next to the nest indicates it was beside a path well-trodden by humans. **Top right:** The nest was very near the water’s edge, close to a lot of litter on the water. **Bottom right:** The swan sitting on the nest seems calmly indifferent to a passing photographer.

Figure 2 The pair of swans with three cygnets on the water – four had hatched successfully but one died

types of relationships we have with nature. I found reasons to take many more photos. Some of these could be used to discuss pollution – for example, it is preferable not to throw bread in the water owing to subsequent contamination from bacterial microorganisms; the amount of litter in some of the shots is also notable. With the path being so close to the nest, it seems likely that litter near the nest had been caused either by lack of thought by onlookers who didn't notice the bins or had no regard for the swans, or by the wind blowing soft litter near to the nest. However, the build-up of waste in the water at the corner of the lake also suggests a stillness of water in that area of the lake where litter accumulated, separate from the flowing currents in the middle. The means of an excellent teaching resource was in the making. Other relationships with nature

Figure 3 Sunset over the lake

that I considered were deforestation and the loss of habitats, and also the variety of life, the trees for oxygen, plants for food and a swan and the strategies she uses to survive. I have many more favourites – of leaves and trees, feathers and birds, conkers, insects, plants, water droplets and, most spectacular of all in my view, the Sun (Figure 3).

Maureen Smith is a biology teacher in Birmingham where these photos were taken with her smartphone. Email: educationaldoctorate123@gmail.com

Professor Sir Colin Humphreys: a report on the diverse work of a leading scientist, crossing boundaries into engineering and theology

Stephen Thompson

Abstract Professor Sir Colin Humphreys CBE has served as president of both the Institute of Materials, Minerals and Mining and 'Christians in Science', while leading materials research throughout a long academic career. This article reflects on his role in posing and answering big questions, both in science and engineering, as well as in humanities and religion. Humphreys would make a good case study for teachers and students to consider how a research scientist can bridge the cultural divide between science and religion.

The names of Joseph Swan and Thomas Edison are writ large in the history of the scientific and technological development of the light bulb, and can be appealed to by teachers who seek to inspire students to persevere in bringing their bright ideas to fruition. Colin Humphreys should be credited in this continuing story in our classrooms, though not simply for his pioneering research work at the Department of Materials Science & Metallurgy of the University of Cambridge (University of Cambridge, 2018). Since his 'retirement' at 75, he has actively continued his research as professor at Queen Mary University of London. Humphreys has been widely recognised for his research in the application of electron microscopy to the understanding of materials including gallium nitride (GaN) and graphene, and he was knighted in 2010 for services to science, particularly his services to science education and promoting STEM in the UK economy. He is a member of the Advisory Council for the Campaign for Science and Engineering.

How do we address the challenges of climate change and the ever-growing global demand for energy? Students can draw Sankey diagrams to illustrate these big problems. Energy generation from fossil fuels is inescapably inefficient and profoundly polluting. Some 20% of UK electricity generation is used for lighting, which wastes heat, while our silicon-based electronic technology approaches the limits of miniaturisation and effective heat sinking. Professor Humphreys's research into the materials science of gallium nitride and graphene enhances our ability to address both problems. He founded the Cambridge Centre for Gallium Nitride in 2000, and then built up and led the team of around 40 scientists characterising and developing the production of very efficient, high-light-output, low-power-consuming, low-cost light-emitting diodes (LEDs) (University of Cambridge, 2014). GaN has further potential to become the basis of the next generation of transistors after silicon devices, saving significant bulk and energy in power conversion.

As Humphreys puts it, '*This is not just good science, it is useful science!*' The commercial implications are obvious, so his intellectual property rights for patented GaN production processes were transferred to a business partnership with the resurrected name 'Plessey' in 2011, and now the Plymouth-based company provides local STEM employment as a major global manufacturer of LEDs in a continuing partnership with the Cambridge GaN research centre. Humphreys explains that what is exciting is that while LED light bulbs now cost around £3 rather than £15, the UK's energy demand should continue to fall by 10%, or £2 billion annually, with an equivalent drop in carbon emissions if sourced from fossil fuels. Globally, this would reduce the number of power stations required in the world by 600, were energy demand to remain stable. Yet it is the production of extreme UV light by GaN devices that holds immediate transformative promise, as this can destroy bacteria and viruses in water to provide safe drinking water supplies across the globe.

Further developments under Professor Humphreys at Cambridge have taken place in the production of graphene, an allotrope of carbon that is a staple topic in the key stage 4 (age 14–16) chemistry curriculum in England and Wales. The technological challenge in producing single or multiple sheets of this highly conductive material has included avoiding the use of copper compounds or other environmental toxins in its manufacture. Humphreys's team solved this problem in a very short time and now he is the founder and a celebrated shareholder in the spin-off company Paragraf, which was set up to develop graphene applications in the next decade, including faster electronics, biosensors and interfaces, lightweight and efficient solar arrays, and supercapacitors (University of Cambridge, 2019). Some of these applications promise to cut electricity requirements by perhaps another 10%. Professor Humphreys's old department at the University of Cambridge is one of those contributing to the 'Making Materials Matter' programme that Jayne Shaw (2019) described in an article in *School Science Review*.

Some further examples of questions that have caught Professor Humphreys's interest include investigations into historical, geographical and scientific aspects of biblical accounts. Is there a plausible scientific explanation for the Star of Bethlehem leading the Magi (so-called 'wise men') from the east to the birthplace of Jesus Christ? (Humphreys, 1993; Bancewicz, 2012). Can the date of Jesus's crucifixion be correlated with a lunar eclipse visible in Jerusalem that caused a blood red moon, as the Bible reports? Astronomical modelling now confirms such an eclipse occurred on Friday 3 April AD 33. Is it possible to develop a rational concept for miracles that fully respects the scientific worldview, and also embraces the most surprising claim of the New Testament, that the crucified and buried Jesus was resurrected from death? In the majority of cases considered, Humphreys concludes that many of the 'miracles' are miracles of timing, and that prayer is meaningful because it enables believers to walk in step with God's timing. However, for Humphreys, Jesus's resurrection is different. This is a (so far) one-off event, and thus not amenable to the empirical scientific method. '*Yet a composer can change the key signature of their music at any time*', says Humphreys, and so the God of creation can change his 'music' to make it even more beautiful, as God wills. We can judge for ourselves whether it is indeed more beautiful, and to what extent Humphreys has stepped up to the challenge that C. P. Snow (1961) set in his 'Two Cultures' Rede Lecture in 1959.

Figure 1 Professor Sir Colin Humphreys speaking at a Faraday Institute event in Cambridge in November 2015; image by Deryck Chan and reproduced under a Creative Commons Attribution-Share Alike 4.0 International license

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Should we teach about the genetics of intelligence?

Michael J. Reiss

Abstract School genetics is changing. Nowadays, students are more likely to be introduced to the idea that many characteristics of organisms, including those of humans, are not determined by the actions of just one or two genes but result from interactions between the products of many genes and the environments of each organism. This article asks whether there is a place in school science for teaching about the genetics of inheritance. There are arguments in favour of such teaching but also risks.

This article asks whether there is a place in school science for teaching about the genetics of inheritance. Biologists have known since the publication of Charles Darwin's *On the Origin of Species by Means of Natural Selection* that inherited variation plays an important role in the various characteristics exhibited by living organisms. Darwin argued that this applies to behaviours as well as to structures and he reasoned that features such as intelligence had also evolved over time as a result of the benefits they had for individuals. The question then arises whether we should teach about the inheritance of intelligence in schools.

The relevance of school genetics

One of the common complaints from many students when faced with their teaching is to claim that it isn't 'relevant'. To most teachers of secondary level biology, there are few topics that could be of more relevance than genetics. Genetics is at the heart of who we are and how we come across to others. Genetics explains how the theory of evolution through natural selection works and it is central to such applied topics as plant breeding and biotechnology. Nevertheless, school students fed on a diet of Mendel's peas and the inheritance of eye colour may not see it that way.

Recently, there have been calls for school genetics to change substantially. In one major study, which ran from 2012 to 2015, an international group of 57 experts, involved in teaching, studying or developing genetics education and communication or working with genetic applications in medicine, agriculture or forensics, attempted to answer the questions: '*What knowledge of genetics is relevant to those individuals not professionally involved in science?*' and '*Why is this knowledge relevant?*' (Boerwinkel, Yarden and Waarlo, 2017). As the authors of this study point out:

> *Results from studies in genetics influence societal practices… It has also become clear that many genes interact to produce phenotypes, that gene expression is modulated by the environment, and that the path from gene to trait is more complex than previously thought. Thus, images of genes and genomes have changed fundamentally … Nevertheless, few of these developments are addressed in biology education: The gap between scientific understanding of genetics and what is taught in genetic education in schools has increased.* (Boerwinkel *et al*., 2017: 1087–1088)

So, if we accept that the gap between scientific understanding of genetics and what is taught in genetics education in schools has increased, is there a place for teaching about the genetics of intelligence? One of my arguments is that there is a surprising disconnect between what most academics in education and what many academics in biology think about the role of genetic inheritance in many areas of human life, including how well children do in schools (Reiss, 2018). Here, I want to look at why there is this disconnect and then examine the core issue of the role of genetic inheritance in school performance. I make three claims:

1. Education needs to stop ignoring the possible role of genetic inheritance in school performance.
2. Genetic inheritance can play a significant role in how well children perform and achieve in schools.
3. This does not mean that children's school performance is predetermined, that is, fixed in advance.

Education needs to stop ignoring the possible role of genetics in school performance

Since Darwin, biologists have accepted that inherited variation plays a central role in the manifestation of the characteristics exhibited by organisms. This acceptance was only enhanced by the early 20th century advances in genetics, followed by the mid-20th century advances of neo-Darwinism and subsequent developments in molecular biology.

As far as our own species goes, this means that just about everything of interest about humans has an inherited component. It doesn't matter whether we are talking about height or body mass or personality or our susceptibility to various diseases or anything else, inheritance generally plays a role. Furthermore, this is also the case for such educationally significant factors as general intelligence, reading ability and examination success.

Many people – including parents and teachers – are happy to accept that children differ greatly in their abilities or potential (e.g. at music, mathematics or sports). However, educators are generally reluctant (e.g. White, 2006) to accept the mounting weight of evidence for the importance of genetic inheritance in school performance. I think that there are a number of reasons for this reluctance – all well intentioned.

First of all, there have been times when genetics has led to major injustices. Various historians of science (e.g. Gould, 1981; Lewontin, 1991) have long since shown how genetics has been used, both consciously and unconsciously, to argue for the inferiority of women, of black and other minority ethnic people and of those not in the upper or middle classes. Faced with this legacy of sexism, racism and general condescension, it is not surprising that educators, who are generally, in my experience, in favour of equity, have rejected genetics as a way of understanding what is important about human nature. As a result, I think that what has happened is that *much of human genetics*, rather than the *misuse of human genetics*, has been rejected. It is as if outdoor activities in general were banned because some outdoor activities are dangerous. The reality, though, is that a *better* understanding of human genetics, not the *abandonment* of human genetics, is what is needed. This is where school science, I believe, has a role to play.

A second reason for the widespread scepticism among educators, certainly in the UK, concerning the importance of inheritance in educational attainment is because of the legacy of Cyril Burt. Burt (1883–1971) was an educational psychologist who played an important role in the development of an examination that survives to this day: the '11-plus'. In England, this optional examination is taken in some parts of the country at age 11 to determine whether students are then educated in selective grammar schools or less academically demanding schools (typically, secondary moderns). Although Burt has his defenders (e.g. Tredoux, 2015), it is generally thought that he systematically engaged in scientific fraud, falsely claiming to have collected data in his studies on the heritability of intelligence (Tucker, 1997). However, the findings that he 'produced' on the extent to which intelligence is inherited were in line with other studies. In other words, even if we ignore Burt's work, there would be no effect on the conclusions to be reached from the early literature about the role of inheritance in the determination of intelligence.

A third reason why educators have tended to ignore the ever-increasing growth in what is known about the inheritance of intelligence is, I think, because of a widespread, often implicit, presumption that *inheritance* is to be equated with *determinism*, a very widespread misunderstanding. I shall address this misunderstanding below; first I turn to the central issue – namely the role that inheritance plays in school performance.

Inheritance plays a role in how well children do in schools

Geneticists determine the extent to which inheritance plays a role in the determination of characteristics in much the same way, whether we are considering the colour of plant seeds, the wool yield of sheep or the mathematical performance of children. Throughout, of course, by 'inheritance' I mean 'genetic inheritance'. Everyone accepts that, for example, family background is important in much that is of interest about us. If one is brought up in a home with lots of books and where reading is valued, it is hardly surprising that one is likely to do better at reading as a child than another child of the same age who has not enjoyed such benefits. I remember as a child, aged about seven, having missed a couple of weeks of school for some routine childhood infectious disease. When I returned, my kind teacher – and I can still recall the concerned expression on her face – said that the class had started on multiplication. '*That's quite alright*,' I reassured her, '*my mother has shown me how to do that*.' Much of the skill in arriving at measures of 'heritability' – the extent to which genetics plays a role – is precisely to do with disentangling, in so far as one can, the complicated and intertwined effects of the environment and the genes.

There are a number of ways in which the importance of the genes in the manifestation of characteristics can be determined. A standard set of practices is as follows:

1. Determine how to measure the characteristic in question.
2. Collect such data from a large number (ideally many thousands) of individuals.
3. Get a measure of the extent to which these individuals have similar genetic constitutions.
4. Get a measure of the extent to which these individuals have similar environmental backgrounds.

The first of these is fairly easy for things like crop yields but harder (in the sense that the measure may not be as robust) for most things of educational interest, such as reading ability or performance in examinations. In particular, there has been a long history of researchers making overconfident measurements of intelligence (Figure 1) that turn out to tell us rather more about the assumptions of the researchers and the cultural similarities between them and their research subjects than about the research subjects' intelligence.

The second requirement in the above list is straightforward, if a bit time-consuming, whether we are talking about crops, farm animals or humans. It's the third and fourth ones that are the most difficult to do, and for this reason a number of human studies have relied on studies on twins (Figure 2). Twin studies are of particular value because there are two sorts of twins – identical twins and non-identical twins. Non-identical twins are no more genetically similar than are any two non-twin siblings but, because they have been born from the same pregnancy, they have shared an early environment that is more similar than that shared by non-twin siblings. Identical twins have an early environment that is at least as similar as that shared by non-identical twins (the caveat 'at least' is needed as there are various types of identical twins depending on how soon after fertilisation the fertilised zygote divided into two); in addition, they are virtually identical genetically. As a result, by looking at the extent to which monozygotic (identical) twins are more similar in certain characteristics than are dizygotic (non-identical) twins, a measure can be made of the heritability of the characteristics in question.

To give a rather clear-cut example: identical twins typically have very similar eye colour – more similar than is the case for non-identical twins. We therefore conclude that eye colour has a high heritability. However, identical twins are not more similar than are non-identical twins in respect of the language (e.g. English, Turkish) that they speak best. This is simply the result of the first language of the family in which a child grows up – whether the child is an identical twin or not and whether the child grows up in its biological family or not. We therefore conclude that the language one speaks best has a very low heritability.

There are various ways nowadays of calculating heritabilities and they give similar values – which is encouraging from a scientific point of view. Heritabilities can lie between close to 0 (e.g. the language one speaks best) and close to 1 (e.g. eye colour). Virtually all human behaviours tend to have heritabilities of about 0.3 to 0.6 (Bouchard, 2004). This means that human behaviours are moderately heritable – not as heritable as height (with a heritability in the West of about 0.9) but more so than religiosity (which has a heritability of about 0.1 to 0.2). Examples of human 'behaviours' are such things as personality, intelligence, artistic interests and the chances of developing a psychiatric illness.

With regard to school performance, a thorough summary of the argument that human genetics plays an important role is provided by Asbury and Plomin's (2014) *G is for Genes: The Impact of Genetics on Education and Achievement* and Plomin's (2018) *Blueprint: How DNA Makes Us Who We Are*. Robert Plomin is one of the long-running advocates of the view that genetics plays a central role in our characteristics. He set up the Twins Early Development Study (TEDS) in 1994 when he moved to the UK from the USA. TEDS is now one of the largest and longest-running twin studies in the world with about 13 000 pairs of twins.

Twin studies have historically been of great value in inheritance studies as they do not require the sort of DNA mapping that has only fairly recently become widely (and affordably) available. Nowadays, other

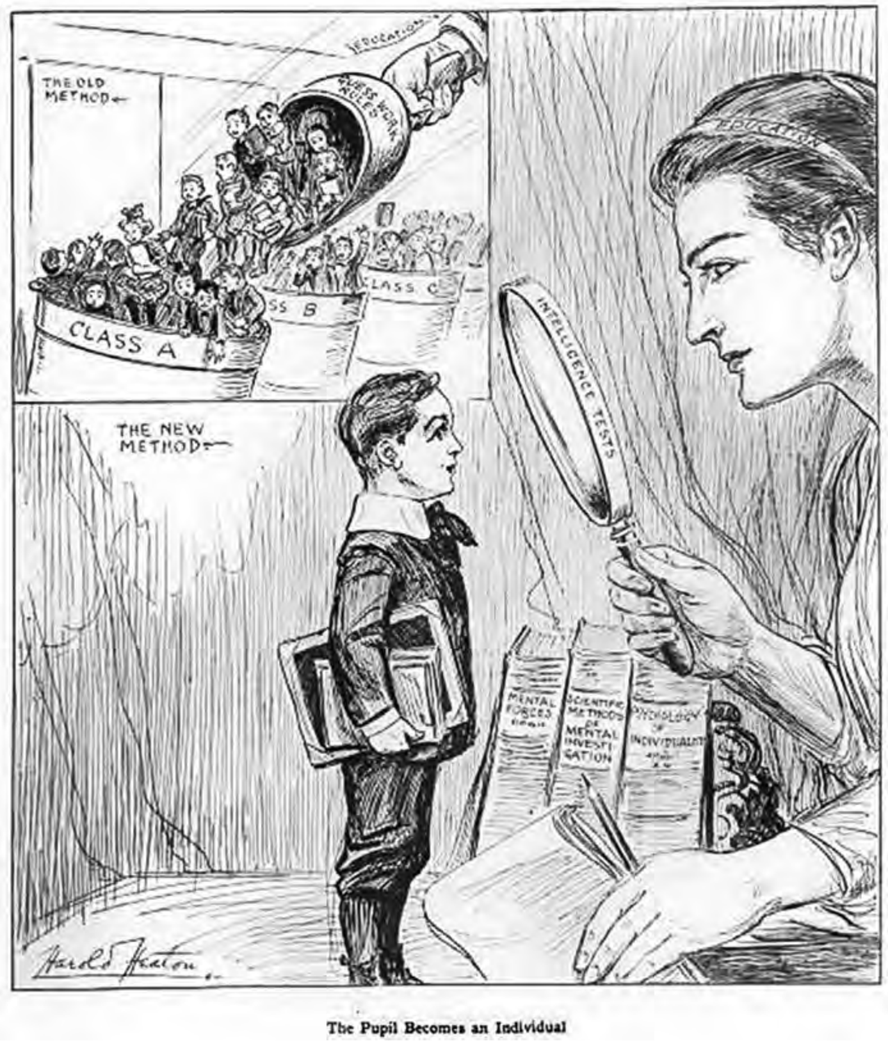

Figure 1 Intelligence testing for use in schools has sometimes promised more than it can deliver (from the cover of the April 1922 issue of the *American School Board Journal*)

Figure 2 Studies on twins have contributed greatly to what is known about the inheritance of characteristics in humans; this photograph shows the 8th Iranian Twins and Multiples Festival, 11 May 2018; image from Fars News Agency, reproduced under a Creative Commons Attribution 4.0 International license

approaches in addition to twin studies are becoming of increasing value in determining human heritabilities. The exceptionally rapid decrease in the cost of DNA sequencing means that it is becoming possible to screen large numbers of people (through genome-wide association studies) to see if they have particular gene sequences that are of interest with regards to particular characteristics. Because they involve large numbers of people (typically in the tens of thousands), genome-wide association studies are good at identifying genes and combinations of genes that have only small effects on the characteristic(s) in question – an important point as it means that one can nowadays find genes that contribute to just about any human characteristics, even if it turns out that the contribution of a particular gene is miniscule and the collective contribution of all the genes examined is very small.

Nevertheless, despite this caveat, it is clear that it is no longer possible validly to conclude that genetics plays no part in the determination of educational success. For example, in the UK, there is a non-trivial genetic component to university examination success (Smith-Woolley *et al.*, 2018). Furthermore, it is not just intelligence and examination performance that are heritable; for instance, genetic factors are implicated in mathematical anxiety (Wang *et al.*, 2014).

There is more to this than genes

Calculating heritabilities and stating that differences between genes are involved in characteristics such as intelligence does not mean that genes alone are important. For a start, there is the obvious truth that genes need the rest of cells to work – on their own, genes can do nothing. Then there is the fact that we could as well talk about the roles that proteins (and other gene products) play in intelligence. The key reason we usually talk about genes is because it is genes that are inherited. For example, changes to protein structure that are not the result of changes to DNA structure are not passed on to the next generation.

Even those who argue strongly for the importance of genetics in the development of human characteristics acknowledge that sometimes genetics plays less of a role than is commonly supposed. Plomin points out that whereas people typically presume that breast cancer is strongly influenced by genetics, in fact it has a heritability of only about 10% (Plomin, 2018) – which may help reassure you if you have a family member who has breast cancer. It is interesting that, despite this low heritability, when one looks at health websites on the causes of breast cancer (e.g. www.nhs.uk/conditions/breast-cancer/causes), having pointed out that being female and older are key correlates, having a close relative who has or has had breast cancer tends to feature strongly. The reality is that there seem to be multiple causes of breast cancer, some of which are still poorly understood.

In respect of intelligence, another reason to appreciate the importance of non-genetic influences is the Flynn effect (2016). Throughout the 20th century, there were large increases in IQ (intelligence quotient) scores over time in just about every country where such data were collected. Each decade, average IQ scores increased by about 2.5–3 points (IQ tests are designed so that at some point in time the average outcome is 100 points). Over the 20th century this increase amounts to 25–30 points, almost 2 standard deviations. A number of factors are believed to contribute – including better health, better education and better nutrition – but the important point is that such data indicate the extent to which intelligence has an important environmental component.

Some of the strongest criticisms of the argument that genes are important determinants of educational success have come from the veteran biologist, Steven Rose. One of Rose's key points is that calculations of heritability depend on the environment – this is well known but easy to forget. A classic example is that human height shows higher heritability in high-income countries than in low-income ones where poor nutrition and disease play a greater role (Perkins *et al.*, 2016). In the same way, Turkheimer *et al.* (2003) concluded that '*in impoverished families, 60% of the variance in IQ is accounted for by the shared environment, and the contribution of genes is close to zero; in affluent families, the result is almost exactly the reverse*' (p. 623). Another point Rose and others make is that gene–environment interactions (possibly of particular significance in human characteristics such as learning) make it even more difficult (less meaningful) to partition out effects between genes and the environment (Rose, 2014).

Nevertheless, and as argued above, there is virtually no doubt that there is a genetic component to intelligence. However, the contribution of any one gene locus is almost always extremely small. Even large numbers of genes considered together typically account for only a relatively small percentage of the observed variation. For example, a recent large study undertaken on over one million individuals identified 1271 independent genome-wide-significant SNPs (single nucleotide polymorphisms) (Lee *et al.*, 2018). However, collectively these only accounted for 11–13% of the variance in educational attainment and 7–10% of the variance in cognitive performance.

Should we teach about the genetics of intelligence?

There is an important risk in teaching about the genetics of intelligence. Because of the common, though mistaken, equation of genetics with destiny (the belief that genes are entirely determinative), students may mistakenly come to think that there is little that can be done to counteract the effect of genes. There is a widespread misconception that one's genes determine one's characteristics. This misconception is probably partly the result of how school biology often teaches classical Mendelian genetics. Introducing students to the simplest cases of inheritance – such as that involved in the characteristics of pea plants, human eye colour, and diseases like sickle cell anaemia and cystic fibrosis – can give the impression that all inheritance is like this. Teaching students more complicated, but more typical, examples of inheritance can help correct this misconception (Gericke and El-Hani, 2018).

Teaching about the genetics of intelligence might provide a good opportunity to teach students about the growth mindset approach. The key argument here is that if learners believe that they can improve their performance (intelligence, subject attainment, skills, examination success or whatever), they will do better than if they believe that their performance is predetermined and cannot substantially be improved (Dweck, 2017). This does not, of course, mean that any of us can achieve whatever we want simply by trying hard – another educational myth that is in its own way as unhelpful as the one that asserts that we differ innately and unalterably in our abilities. As most teachers and parents know, the reality lies somewhere in between, and often in unpredictable ways. Some children really do show a natural aptitude for music, mathematics, ball sports or whatever. But all of us can improve. I may never develop the mathematical abilities of an Einstein or the sporting prowess of Martina Navratilova, but we are who we are as a result of a complicated and lifelong series of interactions between our DNA and our various environments – environments that start from the moment of conception and continue throughout our lives; environments that we partly form as a result of our interests and circumstances.

Furthermore, and especially in relation to intelligence, there isn't a single 'thing' called 'intelligence'. When I was a teenager, I remember taking a number of those intelligence tests one can nowadays find online but were then at the back of various magazines. I did well in the ones that tested mathematical and verbal abilities but poorly in the ones that tested visuo-spatial abilities. And so it remains to this day. I still have to use a map or have someone help me to find the way when I drive to my sister, despite the fact that neither she nor I have moved home for about 30 years. Having done extremely well at chemistry all my school days, I was suddenly floored by much of organic chemistry at A-level. It is difficult to be sure, so many years later, but I think I reacted in the way many people do – I concluded that I had been wrong to think I was good at chemistry and promptly decided to drop it as soon as I could. It is possible that good teaching about both the natural differences between people and the growth mindset approach might have caused me to be less precipitous in my flight from all things chemical towards ecology.

There are a number of arguments in favour of teaching about the genetics of intelligence. The topic provides an example of 'complicated' inheritance – so is more realistic and may be more engaging for students than the simplified stories they often get. It represents cutting-edge science – in that there is still uncertainty about the role of genes in the determination of intelligence and the mechanisms by which such genes act – but it is not conceptually too difficult. It provides a good example of evo-devo, including the role of learning – stories of 'feral' children and children in certain orphanages can fascinate students and help them to appreciate just how crucial our upbringing is for determining who we are and what we can do. Finally, there are natural extensions from learning about what affects intelligence to what affects things like sporting success and musical performance.

All in all, there are a number of things we might want students to learn about the genetics of intelligence:

- Intelligence is not a simple inherited trait.
- Environments and the story of our development are important, as well as genes.
- The non-equation of heritability and determinism.
- Arguments about 'potential' and growth mindset.
- Specific points about the measurement and heritability of intelligence.
- Whether there are likely to be any practical implications of research into the genetics of intelligence – to which I return below.
- Historical instances of the misuse of genetics, allowing for explorations of socio-scientific issues and the role of ethics in science.
- Consideration of the nature of science and the history of science – including disagreements among scientists.

The use of genetics to improve education

Finally, I want to expand on the bullet point 'Whether there are likely to be any practical implications of research into the genetics of intelligence'. As yet, genetics has contributed virtually nothing of any value to teaching. Nevertheless, it is possible that genetics might eventually prove to have some direct educational value. Consider the analogy with medicine. For a long time, understanding the genetics of diseases was of no use in treating them. Gradually, however, certain diseases with a strong genetic component became amenable to treatment as a result of such knowledge or, even better, became preventable. Nowadays we are in the early stage of gene therapy but examples exist from long before gene therapy was even a pipe dream.

A classic example is the condition phenylketonuria. Phenylketonuria is a congenital metabolic disorder in which the body is not able to manufacture the enzyme phenylalanine hydroxylase. As a result, the amino acid phenylalanine accumulates to levels in the blood that affect the brains of infants, resulting in severe mental retardation and other adverse consequences if nothing is done. In 1962, Robert Guthrie invented the test that now bears his name. The Guthrie test relies on the collection of a few drops of blood from one of the heels of a newborn. Individuals found to have the abnormalities in their blood that indicate that they will go on to develop phenylketonuria unless something is done are put on a diet that has as little phenylalanine as possible. Such diets are boring but they are used in many countries and have prevented the development of phenylketonuria in tens of thousands of people.

The example of phenylketonuria is, therefore, an example to do with the genetics of intelligence. What once could validly have been described as a disease caused by a faulty gene has now been largely eliminated though an environmental intervention. In the same way, it is possible that genetics *might* – I don't want to put it more definitely than that – one day be used to tailor intervention programmes more precisely so that – to give just one example – instead of a 4- or 5-year-old simply being identified as slow to start reading, it would be known whether to concentrate on helping the child to distinguish between certain letters, to learn the relationships between letters and sounds, to read consistently and steadily from left to right (for left-to-right languages), and so on. Another analogy would be with spectacles or hearing aids – find the right one and learning can take off.

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Epistemic insight: promoting collaborative teaching between RE and science teachers

Berry Billingsley, Robert Campbell and Matthew Dell

Abstract The compartmentalisation of distinct disciplines limits the opportunities for teachers to work in a collaborative multidisciplinary manner. Workshops such as 'Saviour Siblings' from the Epistemic Insight Initiative encourage students to consider big questions from different perspectives and thus provide a bridge between the religious education (RE) and science curricula at key stage 4 (ages 14–16). This article reports on a collaborative teaching intervention between science and RE lecturers on a secondary PGCE initial teacher education programme. Discussing big questions with their peers proved to develop trainee teachers' beliefs about the power and limitations of science and the value of considering a diverse range of disciplinary perspectives.

The substantive question we explore in this article is whether it is right for a family to use genetic selection to create a child who is designed to save the life of an older sibling who has a life-limiting disease. This question is the focus of a workshop for upper secondary school students that bridges science and RE (religious education) and is designed to develop students' understanding of the power and limitations of science. This objective appears in the National Curriculum in England for science (Department for Education, 2014). However, there is a basis for saying that only a minority of teachers address this objective in practice (Billingsley *et al.*, 2018). The power and limitations of science can further be considered in RE lessons when students consider the ethical implications of science upon family dynamics, the sanctity of life and the extent to which this can be tailored to meet another person's needs.

Our context in this article is initial teacher education, and our aims were twofold. One aim was to create and teach the workshop on 'Saviour Siblings' in a format designed for teacher education. Until this point, the workshop had only run with school students. Secondly, we wondered how future teachers of science and RE would respond to an opportunity to work together to explore a question that is relevant to both of their subjects. Our interest was informed by previous research that outlines the organisational challenges of bringing teachers of science and RE together into one classroom in school (Billingsley *et al.*, 2014). The article also emphasises the importance of teachers' expectations and attitudes around cross-curricular teaching. It highlights concerns shared by many teachers that cross-curricular teaching can prevent clarity about the aims of the session and reduce the efficacy of the timetable to meet the aims of each subject (Billingsley *et al.*, 2014).

Importantly, we argue, the Epistemic Insight Curriculum Framework sets out teachable, assessable and transferable objectives to build students' disciplinary (epistemic) knowledge as they advance through the stages of school education. Epistemic insight is written into the National Curriculum (England and Wales), and in our work it is developed not only within each curriculum subject but also across subjects, to enable students to examine the nature of knowledge in wider contexts and through case studies of real-world problems. Here, we propose that questions that bridge two or more disciplines, including so-called 'big questions' about personhood and the nature of reality, can be brought into a shared classroom space to enable students to analyse and discuss them 'in the round' through a range of different perspectives (Billingsley, 2016). It is an approach that has been advocated as a springboard for teacher collaboration and interdepartmental planning. Consequentially, big questions provide a potential route to overcome entrenched subject compartmentalisation of young people's understanding of science (Billingsley, Nassaji and Abedin, 2017).

Nonetheless, when teaching topics that bridge science and religion, a collaborative teaching approach is not yet commonplace (Billingsley *et al.*, 2014). This article reflects upon how modelling that collaborative teaching informs our teaching practice and the views of the trainee teachers we teach. We describe and unpack a session that bridges science and RE and examine the proposition that a framework exemplifying that views from science and RE are not necessarily in conflict can be of merit to a teacher training programme.

Planning for collaborative teaching

In the initial planning stages of collaborative teaching it was paramount to identify how this intervention could be of mutual benefit to both science and RE trainee teachers.

In the most recent development of the National Curriculum for key stage 4 science (Department for Education, 2014) in England, there is an expectation that secondary students develop an increased understanding of the nature of science and the types of questions that are particularly amenable to scientific methods. Terms that are used to build understanding in schools and/or teacher education include scientism and metaphysics. Several forms of scientism are discussed in the literature; a common theme is a belief that only science contributes to knowledge acquisition (Stenmark, 2001). By extension, a commitment to scientism would suggest that there are no questions that cannot be entirely answered by science (Billingsley *et al.*, 2016). By identifying the limitations of science, students uncover the types of question where science informs our thinking but does not provide a complete answer. It is, therefore, perhaps surprising that Postgraduate Certificate in Education (PGCE) programmes have limited focus on supporting trainee teachers to develop skill sets to identify the limitations of science (De Carvalho, 2016). An understanding of the role of science is, however, not limited to the science curriculum. The GCSE RE curriculum has clear overlap with science, including topics such as the origins of the universe and origins of life. Previous research highlights how religious views can inform science teaching when discussing themes such as evolution (Yasri and Mancy, 2014) or the origin of the universe (Billingsley *et al.*, 2016). Nevertheless, science teachers tend to highlight scientific perspectives as factual (Billingsley *et al.*, 2016). This research, therefore, aims to support trainee science teachers to appreciate the role RE can play in developing answers to big questions, and empower RE teachers to consider the impact of science on a broader range of topics within the RE specification.

There are topics in the RE curriculum where the potential collaboration with science is more subtle. One such example is the '*nature of families, including: the role of parents and children*' (AQA, 2017: 21). Recent changes in UK law that allowed parents to have children to save a sibling can affect the potential roles of children and parents within a family. It further provides an opportunity for students to consider the contribution science makes to answering ethical questions. This topic provided links to both the RE and science curricula and was thus the focus of collaborative teaching.

Methods

The research discussed in this article formed part of a secondary PGCE course. A total of 43 trainee teachers studying the PGCE with qualified teacher status (QTS) course took part in the intervention. The trainee teachers in the study had specialisms in secondary science ($n = 34$) or secondary RE ($n = 9$). The research aims to establish how teaching that utilises the epistemic insight framework informs both the practice of the trainee teachers we support and our teaching practice on a secondary PGCE course.

In advance of the formal intervention, an initial collaborative teaching session asked students to consider if RE and science education were necessarily in conflict. We describe that next and then move on to describe the format of the invention and the data-gathering tools we used to assess it.

The initial collaborative teaching session: contrasting epistemologies

The session was delivered ahead of trainees going on school experience in Autumn 2019. This was a deliberate choice as it forced our trainees to reflect on their schooling to date. The session introduced trainees to crucial terminology such as epistemology, nature of science and nature of religion. Working in mixed groups of RE and science trainees, students discussed their views on a series of statements to uncover whether RE and science teachers held similar or oppositional perspectives. Examples of the statements were: 'There is such a thing as absolute truth' and 'Trust in scientific data is a kind of faith'.

This session asks students for their initial ideas on what counts as valid evidence via questions such as '*Is quantitative data always more valuable than qualitative data?*' and '*How do you know for sure that someone is in pain?*' The session concludes by introducing trainees to the big question '*Are robots alive?*' and asking trainees how they would use different disciplines to answer that question.

Epistemic insight initial survey

The session on saviour siblings was selected from the Epistemic Insight Initiative's range of workshops for schools as a way to deepen trainees' epistemic insight and to introduce them to some of the tools and pedagogies that the initiative makes available. The trainee teachers completed the epistemic insight initial teacher pre-survey, which contained a mixture of 40 Likert scale questions and open-answer responses. After the intervention, trainee teachers ($n = 19$) completed a post-survey. This approach enabled us to identify the initial beliefs held by the trainee teachers and how that affected their approach to answering multidisciplinary big questions. The survey used a mixture of Likert scale questions and open-answer responses to identify trainee teachers' perceptions of science. The questions focused on three distinct themes. Exemplar questions on each theme are outlined below:

- **Personal beliefs**
  How would you describe your position on religion?
  - One day science will be able to predict how a person will behave at every moment.

  - God created the universe.
  - Humans have a soul.

  What makes science distinctive compared with other disciplines?
- **Their schooling as a child**
  In secondary school, I had some lessons where the science teacher and a teacher of another subject taught the lesson together.
  My school explained that science and religion are mostly concerned with different types of questions.
  I enjoyed science at secondary school.
- **Their experiences as a trainee teacher**
  I have seen research on the Epistemic Insight Initiative.
  I am familiar with the term epistemology.
  My experience of epistemic insight has been informed by:
  - school observations
  - feedback on my teaching
  - university whole cohort sessions
  - university subject-specific sessions

One part of the pre-survey attempted to ascertain whether scientism was also prevalent among trainee teachers. The survey included Likert scale statements that formed the following construct:

- One day science will be able to predict how a person will behave at every moment.
- One day we may be able to explain the whole universe using science alone.
- Science is the only valid way to investigate a question.

Analysis and discussion

Perceptions of the relationships between science and religion and attitudes to scientism

The frequency data reported in Table 1 suggests that most trainees are not scientistic when they discuss their attitudes to knowledge on big questions.

These findings corroborate the findings of a survey of 311 years 9, 10 and 11 (ages 13–16) students' perceptions of the power and limitations of science (Billingsley and Nassaji, 2019). The survey of school students found that the majority of those students are not scientistic in their attitudes to knowledge. At the same time, the majority of the 311 students surveyed slipped into scientistic language in their comments and also agreed with some scientistic statements at various points in the survey. These were interpreted as examples of 'uncritical scientism'. The study also reported that a fifth of participating students were labelled as strongly scientistic based on a commitment to scientism across a set of statements about personality and behaviour.

Student familiarity with the Epistemic Insight Initiative

The pre-survey also highlighted the potential benefit of the Epistemic Insight Initiative, with correlations between the statement 'I have seen research on epistemic insight' and the following statements:

- my course has addressed strategies to teach epistemic insight;
- my subject connects with other subjects in the school curriculum;
- I will introduce my students to 'big questions';
- my experience of epistemic insight is informed by university subject-specific sessions;
- science makes it hard to believe in God.

By contrast, as evident in Table 2, the correlations between statements are due to the majority either agreeing or strongly agreeing with the statement.

The aims for the collaborative session on saviour siblings

The second intervention ran in March of 2020. Trainees had completed two separate teaching placements in advance of this intervention. Owing to the global COVID-19 pandemic, the session was run online through university intranet platforms. The session focused on the big question, '*Should science be used to create saviour siblings?*' We adapted the session from a workshop delivered by the first author at the epistemic insight schools conference. The session introduced trainees to changes in UK law that allow parents to undergo *in vitro* fertilisation and use genetic selection of embryos

Table 1 Frequency of responses on sample Likert scale questions

Statement	Number of respondents who…				
	strongly disagreed	disagreed	neither agreed nor disagreed	agreed	strongly agreed
Science is the only valid way to investigate a question	10	22	7	4	0
One day we may be able to explain the whole universe using science alone.	10	12	6	12	3
My subject is best taught as a standalone	16	21	3	2	1
Science and religion disagree on so many things, they cannot both be true.	13	11	14	3	2

Table 2 Frequency of responses for statements that correlated to 'I am familiar with the Epistemic Insight Initiative'

Statement	Number of respondents who…				
	strongly disagreed	disagreed	neither agreed nor disagreed	agreed	strongly agreed
I have seen research on epistemic insight	2	4	15	21	1
My course has addressed strategies to teach epistemic insight	0	1	7	30	5
My subject connects with other subjects in the school curriculum	1	2	1	25	14
I will introduce my students to 'big questions'	1	0	7	22	13
My experience of epistemic insight is informed by university subject-specific sessions	1	1	3	28	10

to create a donor match for older siblings. By introducing trainees to both real-life and fictional stories, the session sought to illuminate the types of question that can be answered by science alone, RE alone and those that are interdisciplinary.

Post-survey

Ten science trainees and five RE trainees completed the post-intervention survey. Owing to the global COVID-19 pandemic, the trainees completed surveys online using a JISC survey platform. The survey used a blend of Likert scale and open-response question to identify shifts in students' beliefs around the interplay between science and religion. Responses to the open question, concerned with trainees' perceptions of the Epistemic Insight Initiative, indicated that trainees were now more confident in constructing big questions. This seemed to be in part linked to the experience of being part of a collaborative subject learning experience. The responses quoted below are indicative of the responses received.

What did you find most surprising about the Epistemic Insight Initiative?

The abundance of links between topics within different subjects. (Female physics trainee teacher)

Why have I not come across this term before? (Male biology trainee teacher)

The vast interconnected-'ness' of interdisciplinary approaches and how this can encourage learning in the classroom. (Male RE trainee teacher)

For me, it is the ability to be able to look at the same question from two different angles and question both sets of knowledge equally. I am surprised by how well it works and how well it could work in a school. (Female RE trainee teacher)

How has this epistemic insight project informed how you plan lessons?

Made me more confident initiating conversations for 'big questions' as there is no one correct answer. (Female physics trainee teacher)

I try to include discussion around moral questions where I can and have always tried to bring in points from other subjects (etymology, history, lining across the sciences even art). (Male biology trainee teacher)

I think I will take the chance to talk about epistemic issues that can be arisen when teaching science, no matter what my belief is, but only to show my students a different perspective, so that they can deduce their own conclusions. (Male physics trainee teacher)

I have been able to draw from areas like science and geography on issues like creation and stewardship and to consider where students may draw on bigger and linked questions. (Male RE trainee teacher)

What big questions would you like to explore in your teaching?

Why is there life in the universe?
Do we need to believe in something in order to do the righteous thing? (Male physics trainee teacher)

How do we find the 'optimum' family makeup? (Female RE trainee teacher)

When does life begin?
How far is too far? (Female chemistry trainee teacher)

These responses highlight that trainees can identify specific examples of how the Epistemic Insight Initiative may inform their teaching. It encourages us to continue to develop opportunities for collaborative teaching in the PGCE programme.

Summary and reflections on how the Epistemic Insight Initiative informs our teaching of a PGCE programme

The initial epistemic insight survey suggests that the trainees we taught are not scientistic in general when answering big questions. Trainees who were familiar with the Epistemic

Insight Initiative were more likely to identify connections with other subjects and aim to develop opportunities to introduce the students they teach to big questions.

Owing to the sample size of post-intervention questionnaires, the conclusions we can make about the impact of this intervention are limited. However, feedback from trainees, which implies that the intervention will inform their future teaching practice, gives increased confidence to continue to develop collaborative teaching opportunities on our PGCE course. Future research aims to add validity to the inferences made in this article.

Further, this research has highlighted how modelling collaborative teaching can foster an enthusiasm for a multidisciplinary approach to teaching. We have overcome the fear that trainee teachers will not see the benefit of a focus on epistemic insight in the same way they will on subject-specific sessions. Observations from those collaborative sessions and responses to statements such as 'science makes it hard to believe in God' have reminded us of the call for teachers and lecturers alike to account for superdiversity of the students they teach (De Carvalho, 2016). The positive findings from this study give us increased confidence to develop collaborative opportunities between science and RE further.

Our future teaching will build upon the sessions discussed in this article to foster opportunities to discuss questions such as '*What do we mean by life?*' In so doing, we aim to support trainee teachers to identify the importance of bridging subjects such as RE and science.

Additionally, the current global pandemic and the challenges of quarantine provide a stimulus to consider the types of question science can answer, such as '*Why have we been placed in lockdown?*', alongside those questions where knowledge from a variety of disciplines must be applied.

We argue, however, that the potential benefit of the Epistemic Insight Initiative is not limited to the overlap between religion and science. A multidisciplinary approach can utilise the overlap between history and science in approaching questions such as '*Why did the Titanic sink?*'

The epistemic insight framework offers opportunities to uncover the '*distinctive nature of science in comparison with another discipline such as history*' (Billingsley *et al.*, 2018: 1124). We plan to expand our collaborative teaching to science and history trainees. Document analysis of the history and science national curricula in the UK highlights that curiosity, enquiry and reference to evidence are themes that are evident in both subjects (Billingsley and Ramos Arias, 2017). We aim to exemplify how science and history define enquiry, the type of evidence they consider, and to encourage trainee teachers to reflect upon whether another discipline can inform their pedagogical practice.

Future directions for research

This project models the potential benefits of embedding cross-curricular teaching in a PGCE programme. To triangulate findings, interviews with PGCE lecturers will identify whether the introduction of collaborative teaching on the PGCE informs their teaching in subject-specific sessions.

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Inspiring Minds: how big questions can build students' epistemic insight and improve attitudes towards STEM

Finley Lawson, Megan Hunt, Daniel Goodwin and Stefan Colley

Abstract This article examines the impact that an 'epistemically insightful' approach to informal science learning can have on students' attitudes, aspirations and perceptions of STEM subjects. It uses interim findings from a research and outreach project, including sustained Saturday activity programmes for ages 14–16 and residential summer schools for ages 15–19, designed to create confident scholars who can engage with difficult philosophical questions raised by current technological advances. The Inspiring Minds project at Canterbury Christ Church University, Kent, UK, delivers informal science learning in schools and informal settings based on an epistemic insight-led approach to STEM outreach and education.

Imagine a series of workshops that introduce teenagers to big philosophical questions about real-world problems, such as the biomedical implications of the nature of human personhood, and the legal and social implications of artificial intelligence. We can suppose that many students will be engaged and that in the course of the discussion there will be opportunities and structured moments when they progress in their substantive knowledge within a number of curriculum areas. At the same time, pinning down an objective for the intended learning does not look straightforward. In this article we report on a project that exemplifies the approach advocated by the Epistemic Insight Initiative, which looks to disciplinary rather than only substantive knowledge as a guide and template for learning.

An epistemically insightful approach supports students in recognising and investigating the links between the disciplines they meet in different curriculum subjects. This deepens their understanding of how knowledge is formed and the relationships between disciplinary and substantive (content) knowledge. Even when engaging students with science in multidisciplinary or real-world contexts there is an emphasis on moving beyond topic-based work (which highlights the content taught within curriculum subjects) to developing students' understanding of the methods, questions and norms of thought of disciplines and their interaction. This article provides an overview of the impact of this approach to Informal Science Learning (ISL) and highlights the ways in which big philosophical questions can be used to frame engagement with a CREST Award (Bronze) and challenge students' misperceptions of the nature of science.

The Inspiring Minds project at Canterbury Christ Church University, Kent, UK, has a number of programmes. This article focuses on data gathered during two of these: 'Inspiring Minds: ISL (Informal Science Learning)', a sustained Saturday activity programme, and 'Inspiring Minds: Summer Schools', a three-day STEM-focused residential course. In both programmes, the combination of the academic sessions with student-led research enables students to develop their understanding of the distinctiveness of science in informing our thinking about big questions, and the importance of framing smaller questions that can be answered by science.

Trying to re-engage students who have decided that science is 'not for them' is one of the biggest challenges faced in STEM education. While the capacity for developing high-quality exploratory science in primary schools is growing, the narrow confines of the exam syllabus and a single 'right way' to perform an investigation means that students who enjoyed the 'tinkering' of engineering or the exploration in the primary classroom can feel, through no fault of willing teachers, that the opportunity for expressing curiosity is missing from the secondary curriculum.

What opportunities do we then have to show students the wonder of science in real-world contexts, engage them with the breadth and diversity of scientific enterprise, and move away from the stereotype that scientists are not creative? In developing an epistemically insightful opportunity we wanted to challenge student misperceptions of the nature of science while also providing them with a meaningful activity, which is where the CREST Award came in. This was work with a purpose, which was 'officially' recognised as science and yet challenged them to engage with science in a way that contrasted with their content-heavy exam experience.

Sitting outside the formal science lessons, Inspiring Minds has the space to allow tinkering, exploration and trial and error, where the error is an opportunity to reinvestigate the task. While this was delivered in a university setting, collaboration between science and humanities departments could allow a similar 'big questions' lunch or after-school club to be developed within schools to achieve some of same attitudinal shifts, without placing the burden for delivery solely on the science department.

Epistemic insight and ISL curriculum rationale

There is well-documented difficulty in encouraging students from diverse socio-economic backgrounds to pursue STEM careers (Archer *et al.*, 2013; Grove, 2013). The Inspiring Minds project was designed to address this by changing students' perceptions of what STEM looks like in real-world contexts. As part of Office for Students (OfS) Uni Connect programme (www.officeforstudents.org.uk/advice-and-guidance/promoting-equal-opportunities/uni-connect), Canterbury Christ Church University developed STEM outreach themed around big questions (Figure 1). The collaboration involves the School and College Engagement team and the LASAR (Learning about Science and Religion) team within the Faculty of Education.

Figure 1 Academic session sheets showing the four big questions examined in the Saturday ISL sessions

Each topic addresses a big question that is informed by scientific thinking and at least one other disciplinary lens. This article describes the 'Does *Siri*™ "just" listen?' session, focusing on the questions raised by artificial intelligence, such as that included in personal assistants like *Siri* and *Alexa*™ (described below), before examining the self-reported impact on the students taking part. It is difficult for students to appreciate the epistemic insight and National Curriculum in England objective to '*understand the power and limitations of science*' solely on the basis of their experience of 'doing' science. We provide practical experiences that we know are amenable to scientific enquiry and that answer questions already framed to be examined by science. Therefore, students need to be supported by explicit teaching on the nature of science (Craven, Hand and Prain, 2002; Schwartz, Lederman and Crawford, 2004; Seker and Welsh, 2005). This teaching can be particularly transformative when based within real-world contexts (Allchin, 2013; Billingsley and Nassaji, 2019; Billingsley *et al.*, 2018).

Academic session description

Each session is designed to re-engage students with science through links to philosophy and ethics, debating, government and politics, and so on. This is not to erase the distinctiveness of the scientific contribution, but instead to provide a hook that then supports students to develop their understanding of scientific enquiry and examine how this may provide a different response to another disciplinary or interdisciplinary approach.

'Does "just" listen?' starts from the real-world experience of the embedded nature of digital assistants and smart technology such as *Siri* (the Apple assistant) and *Alexa* (the Amazon assistant). There has been much media portrayal of these devices constantly 'listening' to the conversations in our houses and workplaces, waiting for their cue word to light up and assist us, but the question this prompts is whether we mean the same thing when we use this term in relation to electronic devices as when it is used of people or animals. Fundamentally, this session explores the nature of human personhood and whether scientific and legal definitions mean that we will one day be attributing personhood to certain smart devices. Using this context as a starting point, the session examines 'what is personhood?' in relation to human and electronic persons. Thus, providing an interdisciplinary discussion that touches on computer science, biology, philosophy and government and politics. While targeted in Inspiring Minds at 14- to 15-year-olds it can easily be adapted for key stage 3 (ages 11–13) or key stage 5 (ages 16–18).

After a starter activity where students establish definitions for key terms such as robot, artificial intelligence, and android, the 90-minute session is divided into four sections: intelligence, autonomy, language and scientific accounts of life. When this is delivered as a longer two-hour session there is additional space to unpack the political and ethical implications.

Exploring artificial 'intelligence'

Following from the starter activity, students are introduced to the idea of the Turing test (the test designed by Alan Turing to establish whether a machine can exhibit 'intelligent' behaviour that is indistinguishable from human behaviour) and consider what we expect from an object that is 'smart'. They hypothesise about areas and topics where a computer programme might outperform a human, before trying out their hypothesis on 'Mitsuku', a Loebner Prize winning chatbot. This activity is managed from the front of the room, ensuring moderation of the questions posed and enabling opportunity to prompt students to express why they are posing their question. This facilitated conversation is designed to prepare students for the next step where they, supported by outreach ambassadors, take part in a live Turing test, with the opportunity to predict whether they have been speaking to a person or a programme. The discussion of their predictions and the results opens conversations around how they tested their hypotheses and the spaces where they found artificial intelligence struggled to replicate human interaction.

How important is autonomy?

This is based on the EU legislation discussion that argued robots would be granted 'electronic person' status once they reached a suitable level of autonomy. Students build small bristlebots (see Bentley, 2020 for a more detailed account) that move 'autonomously' once they have energy (a completed circuit), and compare this to the process involved in the movement of flagellates (single-celled organisms that move via one or more whip-like appendages). Based on this activity and the definition, students investigate the real-world implications of using autonomy as a criterion for personhood, and the ethical and (potentially) legal implications of this definition. This provides an important space to examine how scientific views have changed and the importance of understanding the extent to which science can inform our thinking about big questions but is not able to provide a response to what we 'should' do or the appropriateness of scientific definition in an alternative context.

Does our language about machines matter?

As part of the ISL programme, the question of language tends to be embedded throughout the sections within this workshop. It is used to encourage criticality around the power and limitations of science and develop students' understanding of framing questions appropriately for scientific enquiry. However, the use of media headlines (as illustrated in Figure 2) acts as a strong anchor to highlight the real-world context of the discussion, consolidate the prior learning and lead into the plenary.

Scientific accounts of life

This section acts as both a plenary and a reminder about the nature of science. Students consider the 'MRS GREN' criteria for life and the implications of these characteristics for the previous discussions of autonomy and personhood. They then consider how many of the criteria could be argued to apply (to a greater or lesser extent) to robots. In particular, we address the question of sensitivity to the environment and examine the ways in which this can be replicated in robotics.

This discussion is framed around interaction with a range of 'intelligent' and basic robots (Figure 3), alongside a short video clip from *Erica: Man Made* (https://vimeo.com/209906410) that discusses how the designers wanted to build the android in order to better understand and establish a 'minimal definition' of what it means to be human. This invites students to consider the extent to which science can inform our thinking about human personhood.

This ties back to the question of whether language has the same meaning when applied to both technology and living organisms. However, the pertinent lesson from this section rests in developing students' understanding about the misapplication of science. Drawing students back to the power of scientific enquiry to provide objective answers to narrowly defined questions, they then consider the implications of applying the evidence, or description, outside its intended domain. This takes the students full circle back to the importance of understanding the real-world context when applying scientific knowledge and where the data or evidence may be limited in its relevance or applicability.

As can be seen through this description of an academic session, there is an emphasis on real-world implications

Figure 2 Students critically examine the language used in reporting technological advances

and the power and limitations of science. Each of the sessions explores a big question in a similar way, supporting students designing their CREST research projects to appropriately frame their questions to ensure that they are amenable to science, but, importantly, not to reduce the full response to only a scientific response and thus run the risk of encouraging uncritical scientism.

Discussion

The post-engagement survey showed a positive change in students' perceptions of STEM education (64% stated that engaging with big-question-focused ISL motivated them to study STEM post-16) and in their understanding of the relationship between science and their other curriculum subjects (75%). This shift in understanding disciplinary knowledge rests in the academic workshop explicitly taking an interdisciplinary approach to the big philosophical questions, with students guided to investigate the impact of different disciplinary methods, questions and norms of thought on the response to the questions. Alongside this, the CREST Awards were used to develop students' understanding of the nature of science through the development of their own scientific investigations related to the big philosophical questions and deepen their understanding of what makes a question amenable to scientific enquiry.

The impact of perceived compartmentalisation on students' understanding of the nature or place of science is examined in Billingsley (2017). When this is considered in connection with research on the importance of science capital (Hitchin, Horvath, and Petie, 2017) and identifying science as a field for people 'like them' (Archer, DeWitt and King, 2018), there is a clear case for an epistemically insightful enquiry-based approach. Perhaps the most powerful evidence that a multidisciplinary approach to science has fundamentally changed what science 'means' to the students comes from their interviews. Four key themes arose from the student interview data:

- students' engagement with independent learning;
- students' engagement with science through the lens of big philosophical questions;
- how the style of ISL differed substantially from 'school science';
- the impact the programme had on their interest in HE.

The importance of opportunities to be in charge of their learning was a recurrent theme and is also highlighted by Allchin (2013) as a significant feature in reforming science education. Indeed, some students viewed the opportunity for independent learning as the most valuable outcome of engaging with the project and noted that it had impacted on their learning in school, as they had used the skills to complete homework (including non-STEM subjects). Additionally, the findings echoed those of the Hitchin *et al.* (2017) interview study regarding 'Understanding the broader context of science in society' for example: '*This helped me better understand the world around me and current technology*' and '*It shows how much the Earth is in danger and that we need to do things to help the environment*'.

The development of students' understanding of science in real-world contexts was a key aim of the curriculum planning, but there was initially uncertainty around the extent to which students would engage with the real-world implications. There was, however, a strong recognition by the students of a change in their understanding of the nature of science, which included a broader picture of the real-world opportunities in STEM beyond the classroom. Students spoke of having gained an understanding of how much their daily lives are '*all linked with science*' or that science '*is something better than just sitting in a classroom learning, because it had a bigger impact*', with this wider understanding of science also fuelling some students' aspirations to explore science beyond school.

Independent learning and/or freedom were mentioned explicitly in nine of the interviews. Students frequently commented on the power of them having agency as learners, alongside the achievement or enjoyment of having the freedom to '*do our own research and find out our own stuff*'. This was often placed in comparison to school science that is '*just copying out of a textbook*' or '*exam style questions you've gotta do it like this, this is the answer, this is the wrong answer, you don't really get to have your own opinion*', with one student going so far as to say '*I found it easier* [on Inspiring Minds] *because we weren't being spoon fed but were given the information in ways we understand*'. For some students, the lack of a single answer or method was one of the most challenging aspects of the programme; the understanding that there can be multiple perspectives or answers was a change that they took through to their learning in school.

The opportunity for students to engage in independent learning was also drawn out in the staff interviews as one of the anticipated gains for students: '*the confidence to criticise and analyse in the exam*'. The deputy head teacher noted that the draw to participate was '*introducing students to higher-level thinking and empowering them to be able to access material they wouldn't have normally thought they could*'. When this is placed alongside informal conversations with staff from other cohorts, there is an argument to be made that the starting point, which was new to all (of disciplinary knowledge and philosophical questioning), supported the students to engage at a level higher than they expected themselves to achieve.

Students were asked about their experience of engaging with big philosophical questions. The majority responded with overwhelming enthusiasm for investigating science in this way (in comparison to their experience of school science). Eleven students specifically referred to a preference for exploring science in a philosophical and multidisciplinary way and many felt they would be more engaged in science if it were taught in this manner: '[science] *is very different* [at Inspiring Minds] *like you get more opportunities and experiences like to explore different aspects of it* [science]'. Students reported greater understanding of the relevance of learning science as a result of

Figure 3 Some of the robots used to explore how far autonomy and the characteristics of 'MRS GREN' could be applied to robots

seeing its relevance to real-world and multidisciplinary contexts and being challenged by the diversity beyond physical sciences: '*because this has proved what science actually is, because in school that's what I know science as but then this expanded on what science is and that I enjoyed that part*'. This was often closely linked for the students to the tightly defined format of assessment-focused content delivery, particularly for those who self-defined as 'not science' students but who enjoyed the science experience at Inspiring Minds (for further information on how students were recruited by schools and retained on the programme please contact the lead author for the interim evaluation report): '*I found it a lot better than … school 'cause you can open up so much more different things with it … I'd have to maybe bring some maths in to it for some reasons or some English just … look at it from a different perspective*'. Many students perceived school science as being about '*facts not questions*' and that the content/concept-focused science curriculum didn't allow them enough opportunity to gain a deeper understanding about how things work: '*I prefer to do more looking into how things work, but that's the same with science. I'm just not very good at science*'. Therefore, there appears to be a disconnect for students between their experience of formal science learning and an understanding of the nature of scientific enquiry in real-world contexts.

Conclusion

The findings of this study indicate that students' engagement with the nature and distinctiveness of science and other disciplines across the Inspiring Minds programmes enabled a positive shift in their understanding of science in society as well as their reported future engagement with STEM. The majority of interviewed students self-described as disengaged from science within the formal school setting, but expressed motivation and engagement with STEM in real-world and multidisciplinary arenas. The findings from the interviews, triangulated with the survey results, show a positive association between taking part in the programmes and development of more positive attitudes towards the benefits of science and stronger inclinations to participate more in STEM in the future. Respondents expressed disappointment/frustration that they are '*still always doing this kind of science* [school science]' and '*that's not what we do* [in science] *in school*', highlighting that for some the disengagement is tied not to a disinterest in scientific content or enquiry, but because their experience of science feels disconnected from '*what matters*'.

If big questions do indeed act as hooks for student engagement in STEM (and higher education), then how do we offer students a genuine opportunity to develop their understanding of the nature of science (and STEM-related careers), which captures those not being served by the current curriculum delivery? We argue that, based on this ongoing work and existing research, the use of big questions and real-world problems can engage students widely and, in particular, those in under-represented groups. In addition, an epistemically insightful approach to STEM can effectively teach assessable and transferable curriculum objectives relating to the nature of knowledge. In this way, the project fulfils an aim to address a current gap in provision, whereby many schools neglect disciplinary knowledge in order to focus on content (substantive) knowledge.

The importance and impact of the project has been recognised by the inclusion of Inspiring Minds (both ISL and summer schools) in the TASO (Transforming Access and Student Outcomes in Higher Education) evidence review (Robinson and Salvestrini, 2020), and by inclusion in NEON's (National Education Opportunities Network) Innovation Series (www.educationopportunities.co.uk). There are also links to make with other aspects of STEM education: findings by the Higher Education Academy (Evans, Mujis and Tomlinson, 2015) and the Royal Academy of Engineering (Lucas, Hanson and Claxton, 2014) draw on the importance of multidisciplinary thinking for STEM careers, and the Higher Education Academy report identifies key principles that underpin high-impact student engaged learning, such as real-world mapping of ideas, being guided to independent enquiry and STEM learning placed in a meaningful context. This speaks to the need to continue to develop methods and opportunities to bridge the informal outreach experience and the formal experience within schools.

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Student perceptions of the knowledge generated in some scientific fields

Keith S. Taber, Berry Billingsley and Fran Riga

Abstract Secondary-age students were asked about some science-related careers, using an 'interviews-about-scenarios' technique. This article reflects on students' comments relating to the nature of scientific knowledge. Some comments reflected the aim of science as a means to better understand the world and our place in it. Other comments reflected perceptions of the possibility of applying scientific knowledge to engineer change – something that had great benefits, but also risks. There was also evidence that some students might hold misleadingly positivistic notions about scientific knowledge that may distort perceptions of some areas of scientific work.

This article discusses comments made by students about the value and nature of the knowledge produced in some scientific careers. A perennial issue in science education is the need to balance what might be termed 'science for all' – education to support all of those who live and work in our society, most of whom will not be undertaking scientific work – with the need for a supply of suitable candidates to enter scientific work as researchers and teachers, or other professional work that requires a strong understanding of scientific concepts and processes, such as medical work and engineering (Millar and Osborne, 1998). The need to service the 'STEM (science, technology, engineering and mathematics) pipeline' has been seen as an economic imperative, given the importance of science and technology to the modern economy. Increasingly, however, this is also being seen as an existential imperative, given global concern about such issues as climate change, pollution, food supply, pandemics, power sources and the rate of exploitation of non-renewable resources.

Another well-established tension in relation to the science curriculum concerns the appropriate balance between learning about outcomes of science – some of the typologies, principles, theories, models and laws generated in scientific work – and engaging in, and learning about, the processes of science itself. Understanding the nature of science has been widely recognised as an important aim of education (Hodson, 2014).

Part of the rationale here has been offering a relevant science education for the majority who will not become scientists or engineers, but who should be able to critically engage with claims they meet about medical treatments, consumer choices, environmental issues, and so forth. Yet a strong appreciation of the nature of scientific work is also clearly important for those who will go into such work themselves.

A challenge here is that scholarly accounts of the nature of science (prepared by philosophers or historians, or perhaps sociologists or psychologists) are largely inaccessible to most school students; these experts frame their work through diverse specialist terminologies and may not present entirely consistent accounts. This challenge reflects that of representing, in curriculum accounts, scientific models and theories that may be nuanced, subtle and technical (for example, sometimes being formulated in advanced mathematics). In developing accounts of science for inclusion in the curriculum, whether of the outcomes of scientific work or of science's own nature, it is necessary to make selections (what is important, what can be considered canonical) and to build curricular models of scholarly accounts – authentic simplifications suitable for presenting to students at a particular grade level (Taber, 2008).

The nature of scientific knowledge

Science is at its core an enterprise concerned with generating knowledge, so learning about the nature of science encompasses an appreciation of the nature of scientific knowledge and something of the processes and practices by which it is generated. This theme is *epistemological*, given that epistemology is the study of the nature and sources of knowledge.

Although scholars differ in their accounts of the epistemology of science, there are some commonalities where there is broad enough consensus to inform a curricular model of the nature of scientific knowledge. So scientific knowledge is about the natural world, and is objective in the sense that different qualified observers should, in principle, be able to come to agreement.

We can expect that any inconsistent findings will ultimately be explained (in terms of choices of theoretical perspective, or methodological approach, limitations of apparatus or analytical techniques used, etc.), allowing a rational choice about which findings are sound and which should be discounted.

However, a modern understanding of the nature of science admits the limitations of process that may prevent a commitment to objectivity in undertaking careful, competent scientific work being *sufficient* to come to true knowledge of the natural world. The human cognitive system is inherently biased by the specifics of physiology, and each individual human becomes biased to understand the world in certain ways by their past experiences (Taber, 2014). Experiments can only test those possibilities scientists can imagine. Major shifts in scientific thinking have often been delayed because scientists were primed by their scientific training to think in certain ways and 'see' certain things.

All experimental results underdetermine nature: there are always alternative ways to interpret the same data (even if some alternatives may seem highly convoluted and so unlikely). Moreover, all observations are theory-laden: the way research is set up necessarily privileges some observations over others. Modern science often relies on highly complex apparatus (designed according to particular theories and models) and analytical methods, so an experimental test is strictly of the conjunction of the explicit hypothesis and the theories of instrumentation that are taken for granted in the study design.

There are some quite sophisticated treatments of these ideas, and much historical research offering case studies to demonstrate the challenging nature of scientific epistemology. How much of this material can (or should) be included in school science is an important matter for curriculum developers. Yet it is critical that students are supported in developing epistemological insight. For example, climate change is perhaps the most important issue facing the world, but the science may seem uncertain: some powerful politicians simply deny the science, and scientists themselves talk of trend lines and probabilities, and so seem unable to agree on definite predictions or to commit to explaining specific floods or bush-fire events in terms of climatic change.

Representing epistemology in the science curriculum

So it is critical to persuade young people that science produces robust and reliable evidence-based knowledge that often offers a sound basis for acting in the world, but *also* that scientific knowledge always remains open to challenge. That is, science does not produce some kind of ultimate truth about the world. In particular, there are two features of scientific knowledge that it is important young people should learn about.

One is that *science produces theoretical knowledge*. The products of science are often laws, principles, theories or models. Laws may seem to be absolute: they always apply. But they have only been tested in a limited range of contexts and with measurements to a limited level of precision, so their universality remains a theoretical premise. Indeed, some 'laws' may only strictly apply to theoretical situations (the ideal gas law), or may have acknowledged exceptions (deviations from Raoult's law). Like models and theories, then, this type of knowledge is an abstraction and simplification of the complexity of nature. Scientific concepts can themselves be understood as inherently models (Taber, 2019). For example, students may be forgiven for assuming that the concept 'acid' refers to a clear category of substances that exist in the world, but shifts in the meaning of acid have been motivated by a desire to produce the most *useful* definition to support chemical research, rather than to better characterise some inherent pattern in nature.

While scientific knowledge is, in that sense, theoretical, it derives from empirical enquiry. Traditionally, philosophers of knowledge were classed as rationalists or empiricists, depending on whether they thought the primary source of knowledge was reasoning or experience. Science, once called *natural* philosophy, however, develops theoretical knowledge from the iterative interplay between logical reasoning and experience.

Secondly, *science produces provisional knowledge*. All scientific conclusions remain open to challenge, so, in principle at least, any scientific idea is subject to potentially being modified (or rejected) in the light of new evidence, or even in the light of a new theoretical framework that makes better sense of existing evidence. Being shown to be wrong and changing your way of thinking is not a sign of weakness and failure in science, but a sign of committing to core scientific values.

Student perceptions of science-based careers

A good deal of research has been done considering factors that influence young people's perceptions of careers in science and related fields, including, for example, why there might be gender differences and how home background can influence aspirations (DeWitt *et al.,* 2013). The study drawn upon in this article presented school-age students with short vignettes describing a number of science-related careers and asked them if they would be comfortable in undertaking these different types of work. The students' responses offered insights into their perceptions of these areas of work, including the scientific knowledge generated. It is that data we discuss here.

The context of the interviews

The data were collected during interviews undertaken as part of the Learning about Science and Religion (LASAR) project. Part of the rationale for that project was a concern that young people's attitudes to science might be influenced by common perceptions that science and religion are inherently contrary, something that might be of concern when students with religious faith are considering choices for courses and careers. This stance has been misleadingly presented as 'the' view of science and scientists, and thus has potential to suggest that a young person could not readily become a scientist and also hold religious commitments. The project has explored the extent to which school-age students have the 'epistemic insight' to appreciate why scientists might take a range of stances on how science and religion may be related (Billingsley *et al.*, 2013).

Interviews were carried out in different types of school in England to explore students' ideas about how science and religion might be understood in relation to each other. In one round of interviews, it was decided to incorporate a set of short vignettes describing some scientific careers, chosen because they were thought to have potential to link with extra-scientific values that may be important for young people (a report on this work is being prepared for publication).

Students were read vignettes about the work of doctors, cosmologists, medical researchers, palaeontologists, conservationists, anthropologists and genetic engineers (see Table 1). This was a variation of a technique known as 'interviews-about-scenarios', and offering the vignettes avoided a situation where a student might be asked about an area of scientific work they were not familiar with, or where they might have inaccurate associations with job titles. All research is shaped by the methodology used: here, the vignettes offered a particular and short account of the area of work, and this needs to be kept in mind in drawing conclusions.

Students were interviewed in their schools, after they had offered voluntary informed consent to participate in the study. Fifteen students were asked about at least some of the vignettes (due to time pressures within a longer interview schedule, only seven were asked about the full set, five students were asked about five, and three about six vignettes). Eight of the students were in

Table 1 Scientific careers introduced through an 'interview-about-scenarios' technique, offering brief vignettes of the areas of scientific work.

Career option	Scenario
Medical doctor	Doctors have to be able to deal with very ill people, and sometimes with people in great pain or even dying. In their training they have to dissect human corpses to learn about anatomy. In their work they have to examine people with infectious diseases and, sometimes, horrible injuries.
Cosmologist	Some scientists explore theories of cosmology that try to find out about the origins and history of the universe. The working assumptions in this area are that the universe is thousands of millions of years old, and has slowly developed to have the structure astronomers see today.
Medical researcher	Medical researchers explore the nature of disease and the potential of different treatments to help cure disease or relieve pain and other symptoms. Sometimes medicines and treatments are tested out on non-human animals to see if they are effective. This involves giving animals diseases or injuries then comparing results of different treatments with the untreated animals. Sometimes these animals have to be killed and dissected so that the scientists can examine their internal organs.
Palaeontologist	Palaeontologists study the development of life on Earth by examining fossils of living organisms that died a long time ago. These scientists work with the geologist's models for how different rock formations were formed at various times in the last four thousand million years or so, and with the biologist's model of how all the living forms on Earth today evolved from the same very simple life forms that lived on Earth over three thousand million years ago.
Conservationist	Conservationists try to preserve the different ecosystems on Earth where different animals and plants are found. It is believed that many of the species on Earth are in danger of extinction, and sometimes conservationists recommend killing some animals in certain places because there are too many for the food supply, or because one species (perhaps one not native to an area) threatens the existence of another.
Anthropologist	Some anthropologists study how modern humans have evolved from other species over the last few million years. These scientists assume that modern human beings have been around for between a quarter and half a million years, and that their ancestors were physically different from people today, for example in the size and shape of their heads.
Genetic engineer	Some scientists use genetic engineering to produce new types of animals and plants. They take some of the genetic material from one type of living thing and add it to a completely different type. This can, for example, produce crops that can better deal with pests or cold weather or lack of water.

year 10 of the English system (ages 14–15) and seven were in year 12 (ages 16–17). They are referred to below by assumed names.

Findings: student comments relating to scientific knowledge

For this article, students' responses have been examined to identify comments relating to the epistemic character of scientific knowledge. We found 37 instances of comments made by students that were considered to reflect perceptions of the nature of scientific knowledge. These were characterised into three classes, exemplified below. Twenty comments related to the potential for scientific knowledge to allow us to act in the world to bring about change. Nine instances related to the value of scientific knowledge in helping us understand the world. Eight comments were considered to reflect alternative conceptions of the nature of scientific knowledge. In some of the quotations presented we have slightly 'tidied up' students' spoken comments to aid readability.

Powerful knowledge: applying scientific knowledge to engineer the world

Our vignettes elicited student comments about the utility of scientific knowledge. Denis (Y12) acknowledged how the training experiences medical doctors undertook '*are necessary for improving medical care*' as applicable medical knowledge relied on experience, as '*it's much harder to learn about the human body… from a book or… a model than it is from the real thing and I don't think anything can really prepare you for treating a very ill patient other than treating a very ill patient*'.

Similarly, it was recognised by a number of participants that medical research could have real benefits that made a difference to people. Darshan (Y10) suggested that it was '*for the greater good of mankind, if you did discover a cure for a disease*'. Donald (Y12) noted that '*without that experimentation… We wouldn't get all these cures that we have today… helping other humans*'. Faye (Y12) referred to how '*a really widespread disease or illness… could be solved*' with '*a really important cure*', and Ivy (Y10) noted that '*a few rats dying can save so many people*' , although Holly (Y10) characterised this work as '*killing an animal just to find out why*'. Henrietta (Y10) commented that '*it is a really important thing that we try and find new treatments for things which kill humans… that's a really good profession to be in*'.

Henrietta also noted that the work of conservationists could protect '*endangered species*', although she saw this as correcting '*the effect we've already had*'. Similarly, Ianthe (Y10) suggested this was '*a very, very, very important bit of science. I think that we owe it to every single animal out there to maintain their habitat because we've destroyed it so far*'.

The vignette about genetic engineering, perhaps unsurprisingly, elicited a range of comments about how science could engineer '*beneficial*' (Danny, Y10) changes to the world. Denis saw this as offering '*a huge benefit for the problems we have with world hunger… I think I would quite like that, you know, to try and help out as many people as possible*'. Similarly, Darshan thought this could be '*enhancing… mankind. If you had crops… that could sustain and feed more people… I think that would be a very beneficial profession*'. Henrietta noted how '*it's a positive thing, that crops are influenced to make them more effective because it just means less wastage, and for people in poorer countries… it is their livelihood to farm, then it's a really good thing for them, because it just secures their income really, and it means they're not going to be on the breadline*'.

Donald thought such research offered insurance in case '*we might have a disaster in this world and then therefore the food supply might get cut off… even if like the world changes so that the crops we currently have don't grow, we might then be able to make these new ones… so that if anything, God forbid, did happen, we have a way still of carrying on and still living*'.

Appreciation of the potential for good was sometimes moderated by an awareness that scientific work can have unforeseen and unintended outcomes. Denzil (Y12) acknowledged '*the benefits of it*' but noted '*you do experiments and it can go wrong and could cause quite major problems… it seems very risky*'. Similarly, Ella (Y12) told us '*I could do that because… it will help a lot of people but we can't see what's going to happen… like a lot down the line… it could eventually create something that's poisonous*'. Ivy thought '*it's great you can get better crops*' but '*they have to be careful, because if you make the* [plants] *resistant, the pests become stronger*'. Horace (Y10) warned that '*bad things can happen if you mess with DNA… so I wouldn't like some sort of super bug or something to come out*'.

Fifi's (Y12) response reflected this conditional approval of work that was:

> *improving food sources… and also, kind of like, saving the environment and stuff because they're on about how you can make petrol and things like that from plants. And if you can get crops that grow faster… then it will be more effective and then about pest resistance and disease resistance, but then… if they were resistant to one thing but then they were not resistant to this other thing then they'll all get killed out… but, I think that would be quite an interesting job because… again it's, kind of, helping the world and the environment.*

Ianthe also recognised the potential of genetic engineering to offer benefits, while also noting how she thought the work would be fascinating:

I think it'd be very, very, very interesting. I think it'd be fascinating. I think I can see a lot of benefits of genetically engineered plants and things like that. For example… this woman in… South Arica, she was developing genetically modified maize that had many vitamins in… and that people in poorer, hot, dry, countries could grow.

Fascination: scientific knowledge helps us understand the big questions

Ianthe also thought that cosmology '*would be really, really interesting… fascinating questions*'. In our interviews a number of the participants noted that some of the scientific careers mooted offered the opportunity to better understand what might be characterised as the 'big questions' of our origins. Denis noted '*the sort of fascination of* [cosmology], *you can see images through a telescope… of stars, for example, that aren't actually there anymore… because the light has taken so long to reach it that the star has burnt down by now*'. Declan (Y12) thought '*that's a very interesting field because it is linking what we see now and trying to find the origin of it*'; this was echoed in Dashan's comment that '*Man has tried to explore and find out about his origins so… human curiosity would lead several people into that field of science, which I wouldn't mind doing*'.

Joy (Y10) noted, with regard to palaeontology, that '*fossils are quite interesting because obviously they do share a lot of, like, history and everything*', and Denis thought it was '*quite interesting seeing how different fields of science, for example, can fit together in that relationship. We have the geologists discovering things that explain things, biologists explaining things as well*'. Denis thought '*studying anthropology is quite important when seeing where we've come from*' and Ivy also thought this was '*really interesting, how humans evolved*'.

Alternative conceptions of the nature of scientific knowledge

Some comments suggested that the scientific fields that some participants found most fascinating were seen by other students as offering knowledge of less inherent interest. So, where Denis was excited by the idea of collecting light from extinct stars, Denzil told us he '*wouldn't be interested… I would class it as, sort of, very old science*'. Similarly with palaeontology, two students saw *knowledge of the past* as *passé knowledge*. Ianthe thought '*you're not finding new things, you're not understanding bigger questions. It's not something that I would probably do*', and Henrietta thought she would '*find it a bit too boring*' as '*it's not quite revolutionary enough for my liking. I'm interested in discovering things that are really new, not just kind of confirming things that we already know*'.

There was also a suggestion from a couple of our participants that some types of scientific work could not be objective. Ella thought anthropology was '*a bit subjective*', by which she seemed to mean that if one approached the work with a preformed view it would not be possible to allow for such bias:

It makes sense that we've developed, because it explained why there's so many different kinds of creatures and it just makes sense. But, the fact is I wouldn't be able to fully do it because I already have that sort of belief that we have developed and that's going to get in the way so I might make links between like animals that are completely irrelevant.

Donald thought that scientific work could find evidence to choose between different perspectives, but seemed to see this as comparing a scientific view with a religious view (rather than seeing *any* framework constructed to make sense of, and explain, the data collected as potentially scientific):

Would I like to be like an anthropologist? … I think so yes because you're just finding like evidence to support either one claim or the other. If the evidence you find doesn't support maybe the scientific claim, then it's quite very likely that it will support the religion claim instead. So, either way you're finding evidence that will support one side or the other… I feel comfortable doing that because… the outcome might not be what I think's right but I'm still supporting one side or the other… and it's therefore just allowing each side to go and categorically say well this has to then be the right way… it will give proper detailed answers to how the world was formed and how our ancestors have evolved.

Donald's comments here also seem to reflect a positivistic stance that the work can lead to a definitive, absolute knowledge of our origins. Fifi also seemed to think scientific work should be positivistic, and for this reason had doubts about fields such as cosmology ('*I'd like to do something like that. The only thing is, that with trying to work out the origins of the universe you can never actually really know because you weren't ever there*'), anthropology ('*again, there's always like a, kind of, an element of uncertainty*') and palaeontology:

I like fossils though, I think they're interesting but… I don't think I'd really like it… yet again, I don't think you could ever really know unless you were there… There'll always be an element of uncertainty because… no matter how much evidence you supply… there will always be, like, doubt because of the fact that… you were never there… there'll always be uncertainty.

Discussion

We cannot assume the comments of a small sample of students responding to a selective set of vignettes about scientific careers reflect students' thinking more widely. However, we do consider this study suggests a promising avenue for further research exploring students' perceptions of, and attitudes to, actual STEM careers. Moreover, we hope the reported comments will intrigue science teachers, and encourage them to engage students in discussions about the character of different science-based careers. The impression given in our interviews was that students are very open to learning about, and discussing, what is involved in different areas of scientific work.

It is reassuring to find students telling us that they see some areas of scientific work as inherently interesting and, in particular, that the areas of work sometimes seen as most fascinating related to work that offers insights into the big questions about our origins and place in the cosmos (anthropologist, cosmologist, palaeontologist). There is clearly a hook here for engaging many adolescents: science can help us understand how we come to be here, how we have reached our current state, and how we relate to the rest of nature. Unlike many areas of scientific research, one does not need a high level of background knowledge in a specialist topic to appreciate what motivates the 'big questions', as they are questions about (all) our nature, our identity, our place in the world, our very humanity.

Our interviews also revealed some concerning aspects of students' metaknowledge, their insight into the nature of scientific knowledge. Being aware of potential bias is important for a scientist, *but* such bias cannot be avoided as science is *always* informed by some kind of existing theoretical perspective. Teachers can help students see that objectivity requires an open mind, not an empty mind.

Seeing knowledge of the past as 'old' knowledge surprised us, and it may be useful for teachers to recognise this possibility and be sure to emphasise the ongoing relevance of such knowledge. The elements of positivism found in students' comments reflect previous research (Driver *et al.*, 1996), including earlier findings from our project showing how students struggle to appreciate how scientific theories can be conjectural, yet often offer robust understandings that can be treated as reliable knowledge (Taber *et al.*, 2015). This reminds us that it remains a challenge to help learners understand how scientific knowledge is, necessarily, (in principle) provisional, yet can often become robust enough to inform important decisions. As the example of climate change reminds us, when inaction is itself a risky option, science can offer us the best basis for moving forward, even though scientific knowledge cannot be considered definitive truth.

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