SSR in Depth

June 2022
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The ASE's academically reviewed journal for science education 11–19

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Contributing to *SSR in Depth*

We welcome contributions for all sections of *SSR in Depth*. For reference, a full page of A4 text in the journal is about 800–850 words; including two small figures on a page would bring that down to about 600 words. Articles should be no longer than 4000 words in total, including references.

These can be emailed to The Co-editor, ssreditor@ase.org.uk, or posted to The Co-editor, *SSR in Depth*, ASE, College Lane, Hatfield, Herts AL10 9AA. Detailed advice on the submission of articles and Science notes is available on the ASE website at: www.ase.org.uk/submission-guidelines.

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Health & Safety

For all practical procedures described in *SSR in Depth*, we have attempted to ensure that:

- the requirements of UK health & safety law are observed;
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- appropriate precautions are suggested;
- where possible procedures are in accordance with commonly adopted model risk assessments;
- if a special risk assessment is likely to be necessary, this is highlighted.

However, errors and omissions can be made, and employers may have adopted different standards. Therefore, before any practical activity, teachers and technicians should always check their employer's risk assessment. Any local rules issued by their employer must be obeyed, whatever is recommended in *SSR in Depth*.

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- practical work is conducted in a properly equipped laboratory;
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- any fume cupboard operates at least to the standard of CLEAPSS Guide G9;
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- eye protection is worn whenever there is any recognised risk to the eyes;
- good laboratory practice is observed when chemicals or living organisms are handled;
- fieldwork takes account of any guidelines issued by the employer;
- pupils are taught safe techniques for such activities as heating chemicals or smelling them, and for handling microorganisms.

Readers requiring further guidance are referred to:

Safeguards in the School Laboratory, 12th edn, ASE, 2020.
Be Safe! Health and Safety in School Science and Technology for Teachers of 3- to 12-year-olds, 4th edn, ASE, 2011.
Topics in Safety, ASE, latest version on the ASE website: www.ase.org.uk/resources/topics-in-safety (login required).
Hazcards, CLEAPSS, latest version, and other relevant publications, on the CLEAPSS website: www.cleapss.org.uk (almost all schools, colleges and teacher training establishments in the UK outside Scotland are members, as are many overseas).
Hazardous chemicals database, SSERC, latest version on the SSERC website: www.sserc.org.uk/health-safety/chemistry-health-safety/hazchem_database-2/ (schools, colleges and teacher training establishments in Scotland).
Preparing Risk Assessments for Chemistry Project Work in Schools & Colleges, SSERC, 2020.

Editorial

To ensure that ASE continues to provide all members, especially those in schools, with useful, focused and targeted support, we have changed to a new two-part format for *SSR*. There is now a practitioner-specific journal, *SSR in Practice*, published in both hard copy and online form and comprising commissioned articles from teachers, ASE groups and others, and, published simultaneously, the online journal *SSR in Depth*, which you are reading now. *SSR in Depth* aims to feature more detailed, in-depth science, pedagogical and research content, sometimes generated by ASE groups, sometimes commissioned, and sometimes contributed by individual members and others.

Education for ages 11–19 in England is structured in a way that requires students to learn facts, and the performance of teachers is judged according to how well their students remember and recall those facts. This leads us to question how memory works. The memory is a store for experience and facts, but what is important is how well we can recall those facts and experiences when needed. Do we attempt to keep a record of all that happens every day, and can we discard details we feel are irrelevant? Being able to find what is needed when asked (such as 'where did I put my keys?') is important in many aspects of daily life but has a special relevance to school examinations. Students' success and, by default, the performance of their teachers, is judged through examinations. The first article in this issue, from Kendra McMahon, explores the need for trainee teachers to be open to learning from current research into neuroscience and cognitive psychology but to approach it with a critical mind.

Holding a random store of facts is of course not enough. The store has to be organised or odd items soon get lost. Many details are not worth keeping. Also, many problems require a selection of facts. The skills needed to assemble those facts, for ease of recollection and use, come more naturally to some people than others. However, the development of understanding knowledge and being able to use it to address new problems is essential for progress. Structured teaching helps students to assemble knowledge. This has to come from teachers but, as Fullick and Moore explain in the second article, it helps if the whole biology curriculum is assembled in this way. Their findings are applicable to all subjects, not just biology.

Continuing along the same lines, Christian Moore-Anderson notes the limitations of the short-answer and quick-to-mark questions commonly used for assessment, and provides two simple frameworks for longer-answer assessments in biology that require students to think deeply about biological systems and to integrate different aspects of biology so they come to understand how to learn better.

For over two years, we have had to manage our lives while attempting to avoid COVID-19. The first time we featured some of the consequences in our pages, I indicated with a quick mathematical calculation how social distancing of 2 metres should in theory lead to a very large dilution of someone else's exhaled air, making the chance of catching the virus almost negligible. Rola Khishfe covers this in more depth using a practical activity. This will help the development of many useful techniques in chemistry lessons and with students' scientific literacy.

If we are to teach students successfully, it helps if we can inspire them. Effective education must encourage students to want to learn, rather than being forced to learn. Stephen Rowcliffe reminds us that the COVID-19 pandemic meant education for many students moved to online home learning for many weeks, changing the role of the teacher. Years ago, students would learn through books, teachers and (in science subjects) undertaking practical work. But in the last 40 years or so, access to knowledge via the internet has become well established. However, not all students will be self-motivated to seek knowledge or understanding. Hence the teacher has to find ways to set the agenda, which will help necessary information to be acquired and move education forwards.

Finally we have an article by Keith Chappell, Arif Mahmud and Paul Hopkins, supported by Berry Billingsley and colleagues. They describe a project designed to test the purpose and value of practical work that provided flexible and engaging resources for exploring the 'big questions' of science.

Geoff Auty
Co-editor, *SSR in Depth*

Engaging trainee teachers with neuroscience and cognitive psychology

Kendra McMahon

Abstract Initial teacher education (ITE) needs to respond to the huge increase in research in neuroscience that informs our understanding of learning. Educational applications of cognitive psychology, in particular from the field of memory, are strongly evident in government policy documents in England, but as yet the wider contribution of educational neuroscience is not explicit. ITE needs to open trainee teachers' thinking to these perspectives and what can be learned from them, but also needs to examine them critically and in relation to other forms of educational knowledge and aims. This article explains how one university is taking an interdisciplinary approach to this challenge to develop their ITE curriculum.

As science educators, we know that humans are material, biological beings as well as social, individual people with unique histories. We also know that scientific knowledge is complex, contested and tentative. Importantly, we know what it means to teach learners about both scientific processes and scientific ideas (disciplinary and substantive knowledge), and the fascinations and the challenges that come with that. This means that science educators at all levels of education are ideally placed to work with colleagues to make sense of the explosion of interest in the science of learning and to consider carefully what it means for teachers and students. This article explains how a research group at Bath Spa University, comprising teacher educators, education researchers, psychologists and a neuropsychologist, has responded to this challenge by developing the curriculum for initial teacher education (ITE) in a project funded by the Wellcome Trust.

We argue that considering neuroscience and cognitive psychology brings different perspectives and forms of evidence to existing educational ideas. As professionals, teachers should have an understanding of the different ways in which research can support practice and what it means for teaching to be research informed. It follows that ITE should support teachers in developing sufficient understanding of the contribution of these disciplines. This might challenge, support or extend our current thinking or open new possibilities. At the same time, we need to hold onto the value of educational research and the practical wisdom we have about teaching. Being open minded, but critical, demands our scientific literacy.

This article builds on two previous articles in *School Science Review* (Gittner and Harrison, 2019a; 2019b) that have addressed aspects of the *Improving Secondary Science* report (Holman and Yeomans, 2018) from the Education Endowment Foundation. In particular, it relates to Recommendation 4 Memory: *Support pupils to retain and retrieve knowledge*. The current UK Government position is to highly value established research findings from behavioural cognitive psychology that focus on memory as encoding, storing and retrieving information and experiences. It remains quieter about wider findings from neuroscience and the physical/biological basis of brain activity. This cognitive science lens is evident again in the recent Ofsted research review (Ofsted, 2021) framing of learning as the transfer and consolidation of information from 'working memory' to 'long-term memory' (Willingham, 2009).

Neuroscience essentially supports this two-part view of memory, although the physical basis of memory is still contested (e.g. Camina and Güell, 2017; Gallistel, 2020). But, neuroscience offers different insights too. A key message coming from the science of learning is that cognition and emotion are not separate, they are deeply intertwined, or even inseparable. By providing a wider lens on brain development, neuroscience can contribute to our understanding of the sensory, social and emotional dimensions of learning and what this means for education (see summary by Immordino-Yang, Darling-Hammond and Krone, 2019). Also, there is evidence that conceptual change during science education is not a matter of replacing misconceptions, but of learning to inhibit our everyday ideas when the context demands a more scientific account (Masson *et al.*, 2014). We argue that developing a critical approach includes seeing cognitive psychology as only one way of researching learning.

Initial teacher education – the policy context in England

In November 2019, a new *Core Content Framework* for initial teacher training (ITT) in England was published by the Department for Education (DfE, 2019a). As science educators, it was reassuring to see the content framework giving attention to building on pupils' existing ideas and addressing 'misconceptions'. The emphasis it places on concepts and research from cognitive psychology is striking. For example, in relation to promoting pupil progress it states that trainees should learn that:

> *An important factor in learning is memory, which can be thought of as comprising two elements: working memory and long-term memory.* (p. 11)

The specific recommendations made for teaching practice based on memory research are to avoid overloading working memory by minimising distractions and by breaking content into manageable steps, and only increasing the challenge as knowledge becomes more secure. Trainees should also learn how to sequence lessons with regular spaced practice and retrieval. The findings of the research underlying retrieval practice are that, when compared with rereading a text, being tested on it leads to better retention. There is also reference in the document to 'dual coding', where it says that trainee teachers should practice:

> *combining a verbal explanation with a relevant graphical representation of the same concept or process, where appropriate.* (p. 18)

The use of terms such as 'cognitive overload' and 'retrieval' is very much in line with the view of learning promoted in the *Early Career Framework* for teachers (DfE, 2019b), which is similarly informed by cognitive psychology. For example, it states that teachers should learn that:

> *requiring pupils to retrieve information from memory, and spacing practice so that pupils revisit ideas after a gap are also likely to strengthen recall.* (p. 11)

Indeed, the *ITT Core Content Framework* (DfE, 2019a) explicitly mirrors the structure of the *Early Career Framework*. Both make a useful distinction between trainee teachers having propositional knowledge and putting it into practice: they should '*Learn that*', but also '*Learn how to*'.

Thus there is a clear policy intention to align ITT and teacher development in their early careers.

The similarities should come as no surprise as both the *ITT Core Content Framework* and the *Early Career Framework* have been informed by the *Education Inspection Framework: Overview of Research* (Ofsted, 2019), in which Key Judgement 1: *Quality of Education* is informed by: '*Research on memory and learning*' and:

> *For this, we can draw on a growing evidence base from the 'learning sciences'. Learning sciences is a relatively new interdisciplinary field that seeks to apply understanding generated by cognitive science to classroom practice.* (p. 19)

This introduces yet another term: the 'learning sciences'. According to the International Society of the Learning Sciences (https://www.isls.org), the contributory disciplines include cognitive science, educational psychology, computer science, anthropology, sociology, information sciences, neurosciences, education, design studies, instructional design, and other fields. This draws on a much broader set of research than cognitive psychology alone. The Chartered College of Teaching (2017) similarly selects cognitive science to mention in its Professional Principle 3.4: '*Has up-to-date knowledge of theories and research from the field of cognitive science and understands how these can be used to inform practice in education*'.

These documents seem to be taking the position that, although neuroscience might inform cognitive psychology, it is only at the behavioural level (i.e. the psychological level) that research can directly inform teaching practice. Others have argued that by restricting ourselves to research from psychology, we are missing the potential of a wider range of new knowledge about the brain that includes neuroscience to inform education (Brookman-Byrne, 2017). Also, although a focus on practical applications of research initially seems very appealing, this could support a technicist view of teachers as people who simply receive and implement the findings of others (Winch, Oancea and Orchard, 2015). We agree with Gittner and Harrison (2019a) that teachers should be empowered through access to research to make considered developments to practice in collaboration with colleagues. It is worth noting that throughout the *ITT Core Content Framework* there is considerable, very welcome, reference to the value of discussion and analysis with expert colleagues, suggesting that the value of professional experience and judgment is indeed being recognised.

Some use the term 'cognitive neuroscience' for research into the biological substrates underlying cognition. The range of brain research is huge, not easily divided into distinct areas, and it could be overwhelming. It is certainly unreasonable to expect teachers to become familiar with it all! It is our view that universities should play a key role in managing this complexity by selecting key research and concepts and considering these in relation to existing educational research.

Our starting point was that teachers as professionals should have access to understanding developments across a broad range of research on learning, including neuroscience. Firstly, we saw better knowledge of the brain as a way of challenging 'neuromyths'. Neuromyths are ideas about the brain that have become popular but are not supported by current science. Examples of neuromyths are that people are 'left-brained' and creative, or 'right-brained' and logical, and that strategies for teaching children should be matched to whether they are judged to be visual, auditory or kinaesthetic learners. The VAK or learning styles myth is widespread in the UK and beyond (Gittner, 2018). Science teacher trainees are not immune from belief in neuromyths! In Germany, Grospietsch and Mayer (2019) found that biology trainee teachers held neuromyths in parallel with their neuroscientific understanding.

Secondly, we wanted our trainees to have some tools to raise critical questions about 'brain-based' claims for the value of different teaching strategies and packages. The package *BrainGym*®, in which children were encouraged to do exercises to connect the two hemispheres of the brain (they are already very well connected), is often held up as an example in which science was misused. Current examples where misunderstandings might arise include approaches to emotional self-regulation, in which children visualise their thinking forebrain suppressing their 'primitive, reptilian brain'. Human emotions are not some kind of evolutionary leftover that gets in the way of rational cognition. Attention, curiosity and motivation are vital components of engagement for learning (Howard-Jones *et al.*, 2020). The separation of emotion from cognition has been challenged by clinical findings (of neuroscientist Antonio Damasio). Brain surgery left a patient unable to connect emotions and reasoning and this patient was then unable to make any decisions at all. We wanted to support our trainees in developing their science literacy about the brain. This required supporting their understanding of the knowledge and concepts of neuroscience and also the nature of the scientific processes used to develop such knowledge.

Box 1 Project overview

Cycle 1 (2017/2018): Critical consumers of neuroscience through curriculum development

- Pre- and post-surveys of trainees' views based on Dekker *et al.* (2012).
- Trainee feedback and tutor feedback on critical consumer workshop and science workshop. Trainee focus group analysis.
- Outcomes – teaching and learning materials, better understanding of context and issues with a focus on the value of the interdisciplinary approach (McMahon and Etchells, 2018) and evidence of a reduction in trainee neuromyths and the development of trainees as critical consumers of neuroscience (McMahon, Yeh and Etchells, 2019).

Cycle 2 (2018/2019): Sharing and responding to feedback

- Feedback from other ITE institutions via conferences (ASE, Chartered College of Teaching, Universities' Council for the Education of Teachers, Teacher Education Advancement Network, Primary Science Teaching Trust).
- Trainee and tutor feedback on critical consumer workshop.
- Outcomes – refined open access web-based resources available at www.bathspa.ac.uk/learning-sciences, deeper understanding of concerns in ITE with a focus on tutors.

Cycle 3 (2019/2020): The place of scientific views of learning in ITE

- Dialogues with key agencies and ITE colleagues in 10 institutions (with the University of Bristol).
- Develop guidance for other ITE providers along with more web-based resources.

Design-based research

We took a design-based research (DBR) approach to the project. DBR involves cyclical processes of design, trial, feedback and reflection in a real-life context (Cobb *et al.*, 2003; Anderson and Shattuck, 2012). There are no set methods for DBR. To look at the experience of the trainees we obtained written feedback after sessions to inform the next iteration of the session. We looked at the impact on trainees by a statistical analysis of pre- and post-intervention surveys and through deeper one-to-one interviews. To date, we have undertaken two cycles, and further interations are underway. An overview of the cycles of the project is provided in Box 1.

The first cycle focused on developing new sessions for the PGCE curriculum to support trainees as 'critical consumers' of neuroscience and challenging 'neuromyths'. We then spent a year sharing our ideas with others, gaining feedback and improving the materials based on our own experiences and data.

Taking a critical view by learning more about the brain and brain research

Our work began with challenging the neuromyths held by trainee teachers by looking at simple brain anatomy such as the ways in which the two brain hemispheres are connected by the corpus callosum. We explained to the trainees how views of the brain as having distinct regions for different functions are being modified as new imaging techniques are looking at pathways and networks in the brain (Figure 1). This knowledge can also be used to challenge fixed ideas such as *'I don't have a maths kind of brain'*. The neuroscientist in the project team (Alison Lee) explained that there are different areas of the brain that interact to enable people to do maths: areas for language, areas for spatial awareness and areas for estimating quantity. Large areas of the human brain are 'association cortex' connected by fibres of 'white matter'. Association cortex is where different senses are

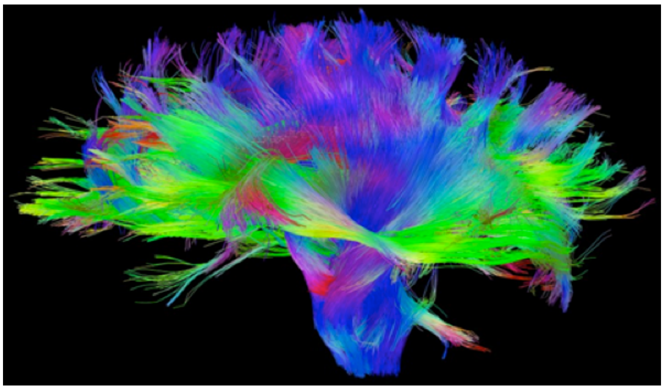

Figure 1 Neuroscience is changing our views of the brain: from regions to networks; image courtesy of the USC Mark and Mary Stevens Neuroimaging and Informatics Institute (www.ini.usc.edu) for the Human Connectome Project

combined to make recognition/memory easier, attention is shifted, planning occurs, and things are learned, stored and reconstructed (remembered). Neuroscience could support a similar argument that doing science involves many different brain areas. As teachers, we were reminded that images are very powerful in shaping our understanding and that we need to choose images of the brain carefully.

As a part of setting up trainees to be 'critical consumers' of brain-based claims in the future, a psychologist in the team (Pete Etchells) introduced us to research on the '*seductive allure of neuroscience*' (Weisberg *et al.*, 2008). This research showed that the addition of spurious neuroscience to an argument makes it more persuasive. The concern is that we are all prone to being persuaded that 'brain-based' claims and products are worthwhile. By building a mock version of the original cognitive psychology experiment into a workshop, the trainees saw for themselves how susceptible we can be. At the same time, they gained an insight into the kind of research that cognitive psychologists conduct.

The next part of the workshop took five claims that the trainees might encounter (Figure 2) and provided them with a scaffold to support them in making a critical analysis of the claim. The scaffold takes the form of *PowerPoint* slides with links to accessible articles and key questions. We have done this as a group activity, with trainees exploring alone and feeding back to the whole class. They could also be used as a source of personal professional development or to work through with colleagues.

Two of the claims address neuromyths (VAK and left brain/right brain); one explores the limits of 'brain training'. The fourth looks at the contested concept of 'growth mindset' (Dweck, 2008) and encourages trainees to think about whether studies have been independently replicated. The last explores the value of 'retrieval practice' as an example of where lab-based cognitive psychology findings have also been tested in classroom settings. Trainees had responded to earlier versions of the workshop by saying that they wanted positive examples as well as what not to do; hence the later inclusion of retrieval practice. However, retrieval practice is not uncontroversial so trainees are asked to think about what kinds of knowledge and views of knowledge it supports.

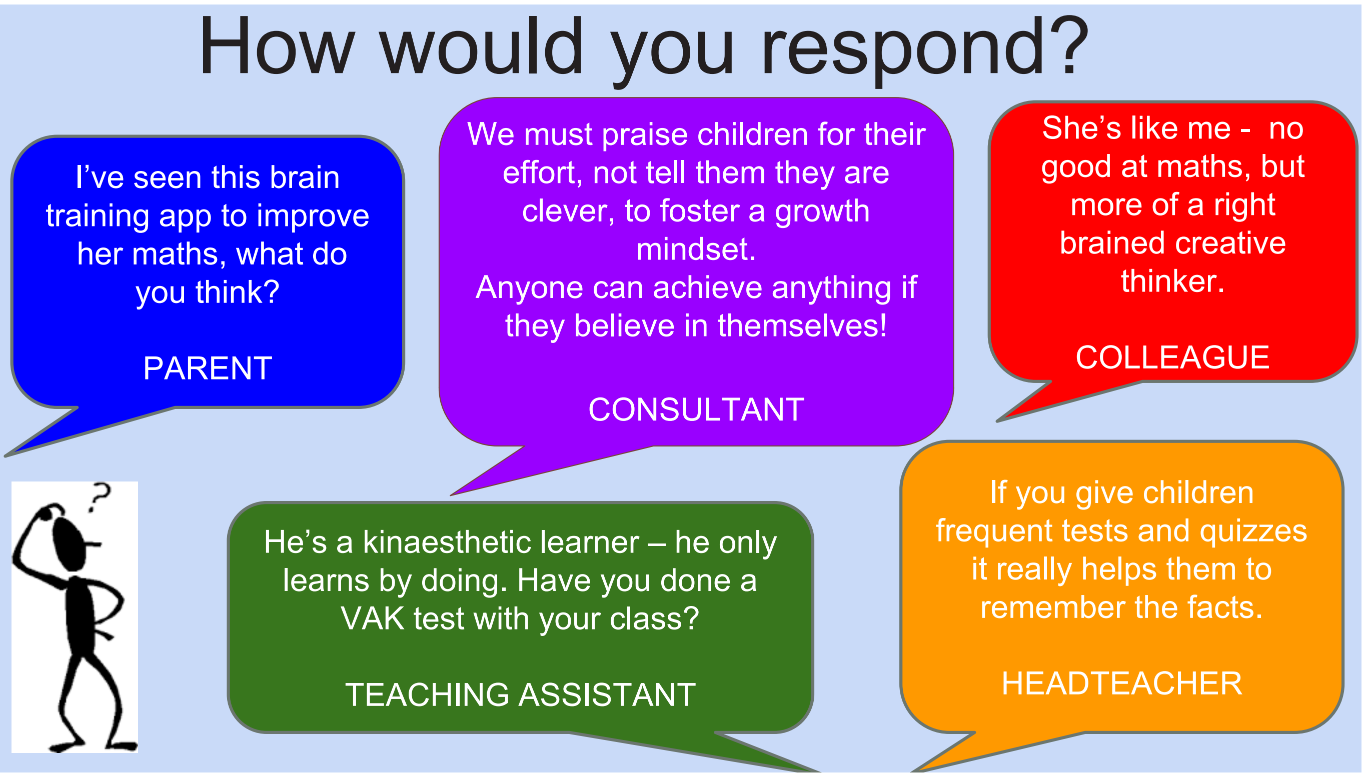

Figure 2 Slide from the workshop resource showing five claims that trainees might encounter

In science education we are always wrestling with the tension between helping pupils to understand the tentative nature of science while simultaneously asking them to accept and recall facts from an unknown authority. We should be thoughtful about how we present and use retrieval practice as a learning strategy and about the discourse we establish around it.

We directly addressed trainee science literacy in their first science session. Trainees considered questions they would want to ask about claims that fish oil supplements support learning. We also developed resources to critique claims about the need to drink six glasses of water a day to enhance brain function. Again in science, a session on the systems of the human body was modified to help the trainees look at the brain in relation to body systems such as digestion and respiration. This was a small step in the direction of an embodied approach by seeing the brain as part of a whole living being, not as an isolated organ.

A further modification to the ITE curriculum was the inclusion of ideas about cognitive load and working memory in a session on SEND, along with a neuroscience-led account that 'every brain is different'. The plasticity of the brain means that a child 'grows their own brain' through their actions and unique experiences. This challenges the idea that categorising children, for example as dyslexic, produces a prescription for teacher intervention and instead recommends a more holistic and creative approach to children as individuals.

The impact of these modifications to the curriculum on trainee thinking were judged by pre- and post-intervention comparisons of trainee belief in neuromyths and their responses to open-ended questions. We found that belief in neuromyths had been reduced, although not totally dispelled, but there had been a significant shift towards uncertainty overall as trainees' ideas were disrupted and unsettled (McMahon *et al.*, 2019). There was also evidence from their written comments that many trainees were taking a critical view of brain-based claims at the end of the course; for example:

> *Don't believe everything you read about the brain just because they have a picture of a brain scan and tell you that scientists say.*

Having refined the curriculum to support trainees to become critical consumers of neuroscience, we have now moved on to look further at what ideas from psychology and neuroscience new teachers should be aware of and what they should know about them. The third cycle of the project has been developed alongside a parallel project led by Paul Howard-Jones and colleagues at the University of Bristol, who are integrating the science of learning into their secondary PGCE courses (www.scienceoflearning-ebc.org). This next phase will be to produce guidance and materials that support engagement with the learning sciences in ITE with critical appraisal of how it relates to existing educational know-ledge and ideas.

Reflections

The value of interdisciplinary work within the team must be emphasised. Cognitive and neuropsychologists were aware of the limitations of their own fields and therefore more cautious and critical of its applications than the educationists, who tended to look for (and find) congruence with our existing ideas. Cognitive psychologists would call this 'confirmation bias'! Working together enabled us all to recognise that each discipline is rich and complex with contested knowledge and varied perspectives. This was evident in the different priorities we brought to the evaluation of research, with psychologists particularly looking for replication of findings and educationists raising concerns about the educational aims and values (McMahon and Etchells, 2018).

What does it means to respond critically to neuroscience-based claims? In the online resources, we focused on developing awareness of the seductive allure of neuroscience and misinterpretations of the science, especially as manifested as neuromyths. We supported scientific literacy by asking trainees to consider issues such as replication of results and any conflicts of interest. We also began to raise questions about how 'success' is measured in research trials. Discussions within and beyond the team opened up further critical perspectives that we wish to integrate into future iterations of resources.

Neuroscience findings are inevitably shaped by the tools that scientists use. Much recent research depends on different neuroimaging techniques that produce images that appear to indicate brain areas lighting up. It is important to understand that some imaging techniques use computers to select and enhance data to generate the image, and the ways in which they do this are determined by the scientists. For example, a scientist will decide the threshold at which brain activity is coloured yellow or red, or left colourless. Scientists will also decide which brain areas to include in the image and which to leave out. This is important, as text with brain images alongside is more persuasive (McCabe and Castel, 2008). Bell and Darlington (2018) give a good account of such methodological issues in the *ASE Guide to Primary Science*.

Social perspectives on education suggest that scientific perspectives can promote a narrow view of learning as knowledge acquisition and argue that education is also about participation, such as involvement in knowledge-based communities (Hordern, 2019). The importance of science capital in influencing pupil career choice that was found by the ASPIRES project (2013) is an example of this. In the same way that being able to decode text is not the same as being a reader, being able to respond correctly in a science exam does not necessarily mean that pupils see science as being for them.

At the moment, the science of learning has focused attention on learners as individuals, undervaluing social/cultural dimensions of learning (as introduced by Vygotsky and Bruner), such as the role of language and the ways in which pupils learn from each other. This might be partly an effect of the current technology: there is only room for one person in a brain scanner! Interestingly, there are moves to make neurological studies of whole classes of children and their teachers, as at the Science of Learning Research Centre in Queensland, Australia (www.slrc.org.au). A focus on individual learning can also promote the 'cruel optimism' of personal responsibility for self-development, while ignoring society-level effects on inequality. This concern that pupils might feel entirely to blame for their own lack of success is one critique of approaches based on growth mindset.

As the project developed, we wondered how trainee teachers' ideas about learning and the brains (and minds) of their pupils might affect practice in subtle ways that are not immediately obvious. Neuroscience offers some alternative insights into what it means to restructure a 'misconception'. It seems that what we actually do is not replace the original idea, but learn to inhibit it to allow new ideas to predominate (Masson *et al.,* 2014). This has implications for how we conceive the outcomes of teaching and learning in science and may have practical implications for how we help children to inhibit alternative ideas – to pause and think slowly (see the 'Stop and Think: Learning Counterintuitive Concepts' project on the Education Endowment Foundation webpages). If trainees look at learning primarily through a selective cognitive psychology lens on memory, what views of learning will they be developing and what will they miss? The emphasis on memory is closely linked with the current emphasis in England on a knowledge-rich curriculum; views of how we learn are always intertwined with what aims of learning are valued.

There are efforts underway to support a wider view of the 'learning sciences' and education. The organisation Learnus (www.learnus.co.uk) brings together neuroscientists and teachers – see their blog pages. You might consider participating in the new online platform 'UNIFIED' (https://unifiededu.org) that brings teachers and researchers together on an equal footing (Hobiss *et al.*, 2019). At Bath Spa University we are continuing to refine our work in ITE and would welcome feedback from school teachers and ITE providers. You can find the open-access materials we have developed to date at www.bathspa.ac.uk/learning-sciences. Please feel free to use them for trainee teachers, early career teachers, by yourself and with colleagues. We not only welcome feedback, but very much need it in order to continue to improve our resources. We have recently considered the ITE curriculum and where the 'learning sciences' should sit within it in response to both the policy context and research, and have developed further materials and guidance for ITE providers that you can find on our webpages. The document on the learning sciences in primary science may be of particular interest. Do get in touch if you would like to help develop one for secondary school science!

As we continue the dialogue between education, neuroscience and psychological perspectives through interdisciplinary DBR we look forward to discussions with policy-shaping bodies and others involved in ITE. Do get in touch!

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A vision for the future of the 5–19 biology curriculum: coherence, learning progression and relevance

A. M. Moore and A. Fullick

Abstract The *Evolving 5–19 Biology* report (RSB, 2021) presents eight key recommendations and a framework for the development of biology curricula for ages 5–19. The framework proposes organising the curriculum in 23 coherent themes that form learning progression pathways. These pathways build answers to seven 'big questions' related to big ideas of biology across three dimensions: practices, concepts and applications. The report is aimed at policymakers but also provides inspiration for teachers looking to redevelop their school biology curriculum. Here, two of the report's lead authors discuss its importance, ethos and intended impacts on biology curriculum policy and teaching.

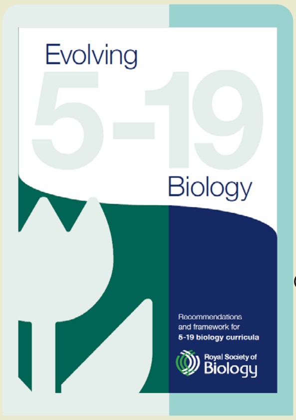
What should pupils' experience of biology at school be? Whatever our path in life we all face challenges, from the global to the personal, and an understanding of biology can provide insight and guide how we respond.

For as long as biology has been taught, teachers have worked hard to prepare and inspire the next generation to care, think, innovate and collaborate, and to understand, protect and improve their health and the world around us. We live in an era of amazing biodiversity and heartbreaking biodiversity loss, of life-saving vaccines and vocal anti-vaxxers, of big data and 'fake news'. How can we ensure the policies and documents that underpin school biology curricula provide young people with the best possible start on the road to becoming the biologically literate citizens and bioscientists of the future? Questions such as this are often asked and are not trivial to answer.

The *Evolving 5–19 Biology* report published by the UK's Royal Society of Biology in autumn 2021 (RSB, 2021) is the result of seven years of work by the society's

Box 1 The report and the Curriculum Committee

Evolving 5–19 Biology can be downloaded from www.rsb.org.uk/curriculum



The report was developed by the RSB Curriculum Committee, which was convened in 2014 and chaired by Professor Libby John (2014–2018) of the University of Lincoln and Professor Jeremy Pritchard (2019–present) of the University of Birmingham

Committee members:

- **Biology curriculum developers** provided insights into past development of national curricula in the UK and elsewhere, and into principles of curriculum design (including coherence and learning progression).
- **Science education researchers** provided an evidence base for decision-making, and insights into effective sequencing of concepts, common misconceptions and the roles of practical and fieldwork.
- **Primary and secondary school teachers and teacher trainers** provided a realistic view of classroom life, of how the written curriculum is translated by teachers and received by pupils, and whether proposed curriculum content would be *accessible* and *teachable.*
- **Assessment specialists** provided advice on whether proposed curriculum content would be *assessable*, how it may be interpreted by examination boards, and on the 'washback' effect that assessments have on what is done in lessons.
- **Representatives from bioscience higher education and industry** provided insights into where school biology may take young people, and into the understanding and competencies needed to study and practise biology beyond school level.
- **Textbook authors** provided insights into how concepts in the curriculum are illustrated and brought to life for teaching and learning in the UK and elsewhere.
- **Students** (sixth-formers aged 17–18 and undergraduate students aged 18–19) provided insights into their experiences of the school biology curriculum and their views of how it could be improved.

The Curriculum Committee received valuable input from a Primary Working Group and Student Curriculum Committee. The report was subject to several rounds of closed and public consultation, including with the RSB's Member Organisations, Special Interest Groups and other committees.

Curriculum Committee (Box 1). The report presents eight key recommendations and a framework to inform the development of future biology curricula for ages 5–19 in the nations of the UK and around the world. In this article, we – two of the lead authors of the report – discuss its content, ethos and the impacts we hope it will have on biology curriculum policy and teaching.

What do we mean by the 'biology curriculum'?

'Evolving 5–19 Biology' provides eight key recommendations to guide future development of biology curricula for ages 5–19, and an organisational framework for the curriculum content.

In the four nations of the UK and in many other countries, policy documents at national level set out what pupils are expected – and *entitled* – to learn in biology lessons at school. These documents form the 'intended' or 'written' curriculum. This is enacted through materials developed by examination boards, publishers and teachers, including specifications and syllabuses, textbooks and other teaching resources, schemes of work and lesson plans, and assessments (for formative and summative use). All of these, together with what takes place in lessons themselves, make up the biology curriculum that is experienced by young people.

The report is none of these things; but it is a precursor to – and intended to provide a strong foundation for – the development of all of them (Figure 1).

The pros and cons of curriculum change

For those who began the adventure of teaching school biology in England, Scotland or Northern Ireland in the last seven years, national curriculum change is something they may have thought about but not experienced. For those who have been in the business a little longer and remember the repeated science curriculum changes and policy churn of the preceding decades, the prospect of another curriculum change may make the blood run cold. Teachers in Wales are preparing to teach a new curriculum from September 2022 (Welsh Government, 2019).

Curriculum change is not necessarily a bad thing. No curriculum is perfect, and our understanding of biology is changing and growing all the time; few subjects are as dynamic, and we ideally want the biology curriculum to keep up and improve so that pupils are well prepared to progress into further study, to use biology in their careers and to navigate biological issues in everyday life. But however well-intentioned, curriculum change – especially at national level – creates disruption in schools, with significant teacher time and budget expended on updating schemes of work, lesson plans, textbooks and other teaching resources. Frequent curriculum change that leaves insufficient time for those at the chalkface to iron out the glitches and develop best practice is the stuff of teaching nightmares. Therefore:

'Evolving 5–19 Biology' is not a call for immediate curriculum change but has been prepared in readiness for the next time curriculum change occurs.

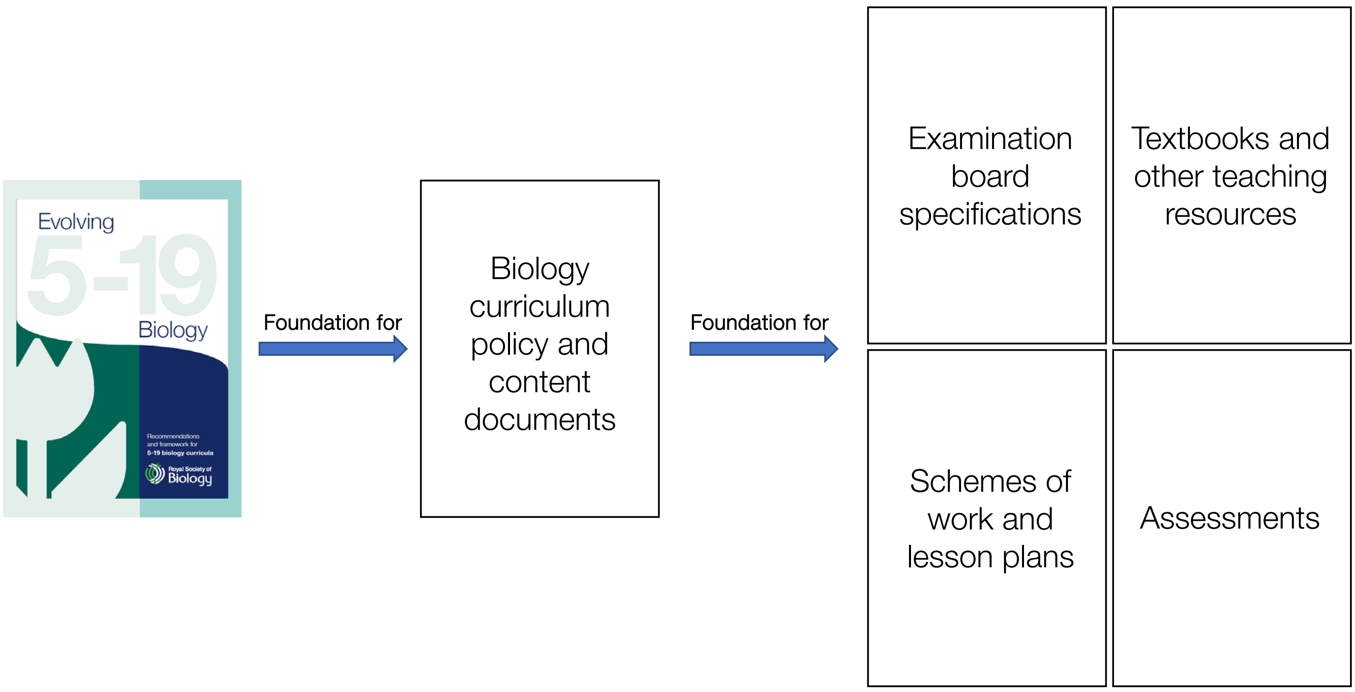


Figure 1 Developed from a strong evidence base, *Evolving 5-19 Biology* provides a well-thought-out foundation for the development of biology curriculum policy documents, which in turn provide the foundation for all the elements used to enact the curriculum in schools

When national curricula are reformed, the intention is never to create a new curriculum that is worse than the one it replaces. But curriculum change is usually subject to political pressures and government timetables; the required pace of change often means there is insufficient time to adequately draw together expert input or to act upon the best evidence from research and international best practice. In contrast:

'Evolving 5–19 Biology' is the product of seven years of detailed thought, research, discussion and wide-ranging consultation.

In England, the biology curriculum at national level has not changed since 2015. That curriculum, and the courses and resources developed from it, have strengths, but they also have weaknesses resulting from the rapid pace at which the last round of curriculum reform was undertaken. The curriculum documents for the different age ranges (Department for Education, 2013a; 2013b; 2014; 2015) were developed by separate teams, often working in parallel; despite the best efforts of those involved in drafting the documents, there was not enough time for sufficient reflection and consultation. Analysis and mapping by the RSB Curriculum Committee indicated that the resulting curriculum lacks continuity (coherence) and clear progression from ages 5 to 19 in key topics and themes in biology (McLeod, 2018).

The big picture: the *Evolving 5–19 Biology* curriculum framework

'Evolving 5–19 Biology' presents a framework that illustrates how the content of biology curricula for ages 5–19 could be organised (or reorganised) for improved coherence, learning progression and relevance.

It might seem obvious to a practising teacher that the biology curriculum should be coherent: the concepts and competencies to be taught should be clearly expressed in the curriculum documents, with continuity and development from each age range to the next so that there is learning progression as pupils move through their education.

Indeed, the need for continuity and learning progression – which we could refer to as 'vertical coherence' – is not a new idea. The seminal *Beyond 2000* report pointed out that the curriculum is not just a succession of facts to be learned, but rather there is a need for '*overarching coherence*' to develop a '*holistic understanding of major scientific ideas and … scientific reasoning*' (Millar and Osborne, 1998). Vertical coherence may not be a new idea, but it is important.

The framework developed for *Evolving 5–19 Biology* (Figure 2) tackles this issue head on, organising the biology curriculum as a series of learning progression pathways that develop, and can be traced clearly, through the age ranges from 5 to 19.

23 themes

The framework organises the biology curriculum content according to 23 themes; the power of the themes is that each one represents a learning progression pathway.

It is envisaged that pupils' scientific understanding is developed as teachers guide them along the 23 pathways (themes) of the proposed curriculum framework.

Teacher feedback together with evidence from research on learning progression and comparisons with international curricula suggested it was most appropriate for some learning pathways to start at age 11 – for example the pathway for learning about 'Cell structure and function'. But most of the pathways begin in the 5–11 age range and all continue through the upper age ranges. Learning at age 5 about changes through the seasons, for example, could be one of the first steps in the 'Environmental interactions and processes' pathway that by age 19 has progressed to encompass quite complex ideas of ecology. The learning pathways are continuous and traverse the transitions points between the age ranges covered by the curriculum. At each stage, there is a clear sense of what the learning is building upon and what it's leading to. The report provides summaries of the expected learning in each age range for each theme.

A curriculum designed with this sort of 'vertical coherence' built in provides a strong foundation for learning progression – but progression towards what, exactly?

Seven big questions

In the framework, the 23 themes build answers to seven 'big questions' of biology.

The *Beyond 2000* report referred to progression towards understanding of '*major scientific ideas and … scientific reasoning*'. But what are these major ideas? Prominent thinkers in science education theory have identified 'big ideas' that science education should explore (Harlen, 2010; 2015). These big ideas are the essentials that our understanding of biology, chemistry and physics could be boiled down to. The detail of each of these big ideas is *too big* to teach in one go; understanding of each big idea is built up gradually by exploring a series of smaller key concepts in an appropriate sequence. This approach underpins the learning progression pathways proposed in *Evolving 5–19 Biology*.

The seven big questions in our framework were derived from the big ideas identified by Harlen and her

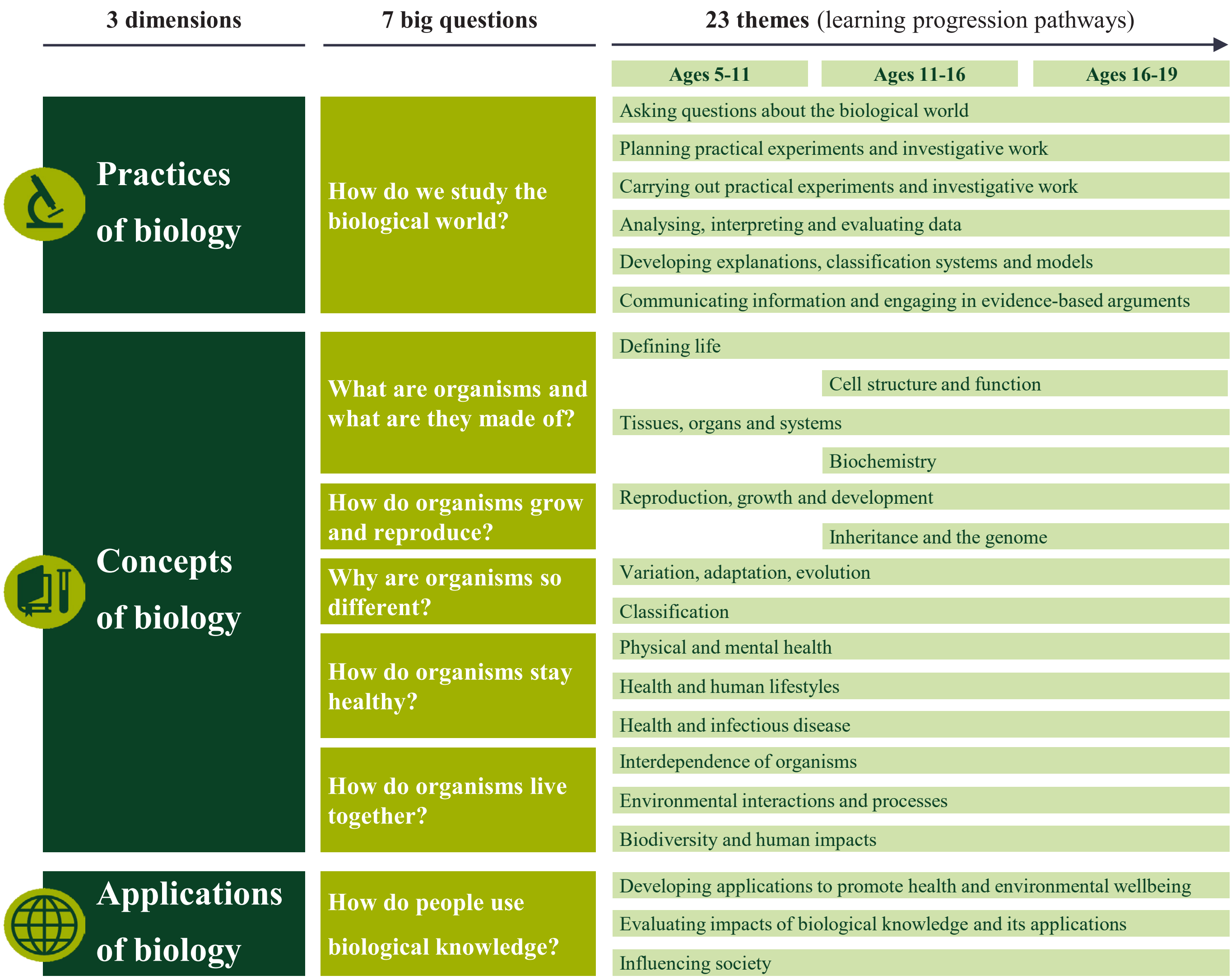


Figure 2 The *Evolving 5–19 Biology* framework shows how the content of biology curricula for ages 5–19 could be organised (or reorganised) according to 23 themes (learning progression pathways) that build answers to seven big questions of biology across three dimensions

colleagues. It is challenging to adequately express and explain the big ideas before pupils have amassed a reasonable body of biological understanding, which means the big ideas are less useful as an organising device for the science curriculum in primary school. In discussions with our Primary Working Group, we reworked the big ideas of biology into the seven 'big questions' of our framework, with each question deliberately worded so that it could be asked and explored by anyone with any level of biological knowledge. At each stage of the curriculum, teaching aims to help answer the big questions in a way that is meaningful and appropriate for the age range. The answers are expanded upon and become more detailed as pupils progress along the learning pathways.

The 23 themes are not intended to be exclusive pathways taught in isolation from one another. Rather, multiple pathways together help pupils to explore and build answers to each big question. For example, in the 'Defining life' pathway at ages 5–11, pupils may learn about characteristic processes that occur in living things as *functional* criteria for defining life (e.g. movement, reproduction, sensitivity, control, growth, respiration, excretion and nutrition); from age 11 they learn in the 'Cell structure and function' pathway that living things are made up of one or more cells and what these are, thus adding a *structural* criterion for defining life and enriching the answer to the big question 'What are organisms and what are they made of?'

Three dimensions

The 23 themes and seven big questions of the framework span three important dimensions: practices, concepts and applications of biology.

The aspiring bioscientists and biologically literate citizens of the future need to explore more than just core concepts of biology. Young people are surrounded by a barrage of science and pseudoscience, of claim and counterclaim, continually delivered to their phones, and they are judged by their responses and their choices. Young people are entitled to a biology curriculum that enables them not only to experience the explanatory power of biology, but also provides understanding of how bioscientists develop these explanations and of how biological knowledge is applied and impacts the world.

As with the need for the curriculum to facilitate progression in understanding of scientific concepts, the need for the curriculum to develop pupils' understanding of scientific practices and reasoning is not a new idea, but it is important. It was recognised, for example, in *Beyond 2000*, in Harlen's *Big ideas of science education*, and in the AT1, Sc1, 'How science works' and 'Working scientifically' strands in successive versions of the National Curriculum for science in England since 1989. A recent review of research in science education conducted by England's Office for Standards in Education, Children's Services and Skills concluded that '*a useful framework for constructing science curricula makes the distinction between substantive knowledge*' (the second of our dimensions) and '*disciplinary knowledge*' (the first and third of our dimensions) (Ofsted, 2021). The three dimensions proposed in *Evolving 5–19 Biology* resemble the three-dimensional approach adopted by the Next Generation Science Standards in the USA (NGSS Lead States, 2013), which resulted from extensive research on developing pupils' science literacy (National Academy of Sciences, 2012).

It is intended that pupils' practical and mathematical competencies will be developed across the 23 themes and three dimensions of the proposed curriculum framework, as will their understanding of a number of cross-cutting, emergent themes (including: how the living world is made up of systems nested within systems at different levels of organisation from molecules to ecosystems; how matter, energy and information flow within and between these systems; and the importance of stability and change).

A united front

The Royal Society of Chemistry and Institute of Physics have developed similar curriculum frameworks.

Despite differences in the disciplines, the principles that drove the development of the *Evolving 5–19 Biology* curriculum framework could also be applied to the development of curricula for chemistry and physics. The UK's Royal Society of Chemistry (RSC) and Institute of Physics (IOP) convened curriculum committees at the same time as the RSB, and through a combination of convergent evolution and deliberate cross-pollination they have developed similar frameworks to show how the content of chemistry and physics curricula for ages 5–19 could be organised (Edmunds *et al.*, 2018; McLeod, 2018; Gibney, 2018; Tracy, 2018; Royal Society of Chemistry, 2020).

Testing and refining: our exemplification of the framework

Organising the 5–19 biology curriculum as a series of learning progression pathways that develop understanding of big questions in biology may be a nice idea, but is it really possible to organise a curriculum this way?

The appendices to *Evolving 5–19 Biology* provide an exemplification of our curriculum framework, in which we have populated the 23 themes with detailed content statements at each age range – adding meat to the bones as proof of the principle.

The exemplification is not intended to be a ready-made curriculum, but is a proof of principle of the framework and provides guidance for future biology curriculum developers.

Development of the exemplification began as a mapping exercise, in which the biology content statements from the current National Curriculum documents in England were organised according to our themes (described by McLeod, 2018). Populating the themes with this content helped us to refine the number and nature of the themes in an iterative process, by enabling us to ask and respond to questions such as:

- Is it possible to populate each theme in each age range with content statements that are: age appropriate; scientifically correct; teachable; assessable; and up to date but expressed in sufficiently future-proof terms that they will not imminently need to be re-written?
- Does the content form a coherent learning progression pathway for each theme, without gaps and without unnecessary repetition across age ranges?
- Is each piece of curriculum content relevant to the learning progression pathway and does it earn its place by helping to answer the big question?

Although we started with content statements from the current National Curriculum documents in England, we reorganised, re-wrote, deleted and supplemented them until our answer to all of the above questions was 'yes'.

The third of the questions is particularly important when considering the view of many teachers that school biology courses are too content-heavy. Consultation on curriculum content inevitably elicits campaigns for particular bits of biology to be included, which can lead to an overstuffed curriculum. The approach of building learning progression pathways to answer big questions brings focus; when viewed through this lens, it may be decided – for example – that learning how monoclonal antibodies are made in the lab (as GCSE biology pupils in England are currently required to do) is not necessary to satisfactorily answer the big question 'How do organisms stay healthy?' at ages 14–16.

The exemplification also helped us check aspects of what we might call 'horizontal coherence' – the degree of alignment between all the things that contribute to what pupils are learning at a particular point in the curriculum. For each concept introduced in the exemplification, we checked that all the necessary supporting ideas were either introduced at the same stage or had been introduced at an earlier stage of the framework. In conjunction with the RSC and the IOP, we also checked the alignment with the necessary supporting ideas in the chemistry and physics frameworks. If, in the future, the framework or exemplification are used to develop a biology curriculum for schools, similar checks will have to be made against the curricula for mathematics and other subjects to ensure that learning in biology is appropriately supported by, builds upon and supports learning in other disciplines at each stage.

The eight recommendations

The recommendations are intended to promote good practice in biology 5–19 curriculum development.

Evolving 5–19 Biology makes eight key recommendations to guide future development of biology curricula for ages 5–19 (Figure 3), which capture the essence of the myriad discussions, expert inputs and consultations that took place throughout the first seven years of the RSB Curriculum Committee's work.

All eight recommendations influenced the development of our curriculum framework, and recommendations 3–8 informed the development of our exemplification.

Expressing the written curriculum with clarity, and with teachability and assessability in mind, as called for by recommendation 7, helps to ensure there can be good alignment between it and the various textbooks, lesson plans and assessments developed from it in the future (another aspect of 'horizontal coherence').

Recommendation 8 relates to the relevance of the curriculum, but poses particular challenges in a fast-moving discipline such as biology. For example, in 2015 CRISPR genome-editing technology was named '*Breakthrough of the Year*' by the journal *Science* (Travis, 2015), immediately making the references to more traditional genetic engineering techniques in exam specifications and textbooks look a bit behind the times; but for how long will CRISPR technology represent the cutting edge? Each redevelopment of a biology curriculum offers the chance to reflect the latest developments in the field, but if specific examples are enshrined in high-level curriculum documents, they limit innovation

1	The biology curriculum should develop pupils' understanding in three dimensions: practices, concepts and applications of biology.
2	The biology curriculum should aim to develop pupils' understanding of big ideas in biology, to help answer big questions about the biological world.
3	The biology curriculum content should facilitate coherent learning progression from age 5 to age 19.
4	The biology curriculum should provide pupils of all ages with ample opportunities to engage in practical and investigative work, including in the field.
5	The biology curriculum should provide pupils of all ages with ample opportunities to learn about plants and other organisms, in addition to humans and other animals.
6	The development of biology curriculum policy, guidance and content should draw upon previous curriculum development work and evidence from research, where appropriate.
7	The biology curriculum content set out in policy and guidance documents should be clear, teachable and assessable, while allowing scope for innovation in delivery.
8	The biology curriculum should be contemporary yet durable.

Figure 3 A summary of the eight key recommendations of *Evolving 5–19 Biology*

in teaching and assessment, and become hostages to fortune that could necessitate further rounds of disruptive curriculum change.

In the wording of content statements in our exemplification, we strove to strike a balance between currency, future-proofing, and allowing for scope in teaching and assessment. The following is an example from the exemplification of the 16–19 age range of the 'Inheritance and the genome' progression pathway:

> *Genetic technologies lead to increased understanding of organism function and facilitate development of new industrial and medical processes, including synthetic biology.* (RSB, 2021)

Individual curriculum content statements aside, the organisational framework of big questions helps to future-proof the curriculum. The big questions, and the big ideas of biology they relate to, are unlikely to change any time soon. To use a biological analogy: if the curriculum was a tree, the framework of learning progression pathways that answer big questions would be the trunk and branches; just as trunks and branches are made up of cells, the learning progression pathways are assembled from a series of essential key concepts; while specific examples, contexts and teaching approaches may come and go like the leaves of a tree through the seasons, the underlying framework of learning progression pathways – like the trunk and branches – should be better able to stand the test of time. The framework provides scope to cover new and exciting bits of biology while clearly identifying the essential learning that will support pupils on their various journeys into further education, work and everyday life.

Who is *Evolving 5–19 Biology* for?

The framework of three dimensions, seven big questions and 23 themes (learning progression pathways) could be used to organise a new biology curriculum or reorganise an existing one. The recommendations, framework and exemplification are principally intended to guide policymakers and curriculum developers working at national level the next time the 5–19 biology curriculum is reformed. But they could also provide guidance to schoolteachers and science departments as they redevelop or reorganise their own biology curriculum.

The big questions of biology, the big ideas they relate to, and the themes through which teachers and pupils explore them, are relevant not just in the UK but wherever 5–19 biology is taught. Applied, technical or vocational course could draw upon subsets of the themes.

A vision for the future

Just as the work of the RSB Curriculum Committee did seven years ago, this article began with questions:

- What should pupils' experience of biology at school be?
- How can we ensure the policies and documents that underpin school biology curricula provide young people with the best possible start on the road to becoming the biologically literate citizens and bioscientists of the future?

Evolving 5–19 Biology cannot provide all the answers. We know it will prompt discussion and debate, but it is the product of seven years' work and significant investment of time and expertise by those on the RSB Curriculum Committee and all those we consulted. It is also the product of many litres of tea and coffee, and a mountain of sandwiches!

After experiencing the pace at which the science National Curriculum in England was reformed in 2013–14, the RSB resolved to take a proactive rather than reactive approach to answering these questions. We have taken the time necessary to draw together expert input, to reflect upon the best evidence from research and international best practice, and to consult widely on our proposals.

Evolving 5–19 Biology can guide the policymakers of the future who will be reforming the 5–19 biology curriculum at national level, and the curriculum developers who will be charged with translating policy into practice. It may also inspire teachers in the present who want to redevelop their own biology curricula in schools. Our sincere hope is that this vision of a 5–19 biology curriculum founded on the principles of coherence, learning progression and relevance will positively impact biology curricula in the nations of the UK and around the world.

Acknowledgments

We offer our heartfelt thanks to the Committee, past and present, and staff in the RSB Education Policy team, inluding Lauren McLeod, Sarah Dalmedo and Helen Mitchell, for all their hard work, time and expertise in bringing the vision behind *Evolving 5–19 Biology* to life. We would also like to thank the many experts from the fields of teaching, research, industry, and the wider bioscience community who contributed invaluable insights via discussions with the committee and consultation responses.

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Measuring and fostering biological thinking beyond short-answer questions

Christian Moore-Anderson

Abstract Short-answer questions are commonly used for assessment in secondary biology education, but their scope limits what can be observed. If a curriculum intends to encourage students to think deeply about how biological systems function, or to integrate physiology, development, evolution and ecology, then longer-answer assessments are required. This article presents two simple frameworks that can be used for assessing biological thinking beyond short-answer questions over educational stages and different contexts, to complement standardised testing. Additionally, by sharing the frameworks with students, it is postulated that they will understand better how to learn in biology.

A curriculum must endeavour to provide students with a learning experience that will allow them to form an interconnected view of a subject domain. The role of assessment, in addition to recognising the learning of students, is to enable a feedback loop between curriculum design and pedagogy that can ensure that pedagogy is adjusted to meet the goals of the curriculum.

In their book, *Leading Modern Learning*, McTighe and Curtis (2019) argue for new methods of assessment and student-performance reporting in education. Using their backward design model, curricular design begins with the desired learning outcomes (which may go beyond success in standardised testing, such as GCSEs) and moves on to the evidence that could be collected to measure them. They summarise this as the I-O-I model: Impact (student outcomes), Outputs (evidence of these outcomes), and Inputs (pedagogy), in that ('backward') order of design. When content, or standards, come first in planning, they argue, an overcrowded curriculum and pedagogy of content coverage often emerge.

Current biology courses, such as GCSEs in England (ages 14–16), generally stipulate content to be learnt, which is then assessed with short-answer questions. Isolating content in short-answer questions can promote a fragmented view of the curriculum, which may lead to beginning curriculum design with the content that must be learnt, rather than the overall desired learning outcomes. Hence, planning for how we want students to think, or see the biological world, may be low in priority. Internal assessment and reporting of students are often skewed towards forming a prediction of the potential GCSE grade students may achieve, or a relative cohort position (student ranking) after sitting an exam. While such systems may report how students are achieving relative to their peers, do they measure everything a biologist would value?

In two of my publications (Moore-Anderson, 2021a; 2021b), I argue for learning outcomes that typically go beyond what is tested in GCSE exams. The first (2021a) provides a framework for teachers for planning and assessing for a student's understanding of biological systems (systems thinking). The second publication (2021b) provides a framework for biology curricular design to integrate the (often dominant) learning of physiological systems with their ecological and evolutionary facets. This framework for integration was intended to foster a student's capability to develop an enquiring mind about the nature they observe around them by focusing thinking on the whole organism through the lenses of evolution, ecology, physiology, and development. I concluded that '*with the use of the framework and the constant practice given to students …* [they] *may come to acquire this line of seeing as a disposition, a biologist's gaze that can facilitate them in reading nature*' (Moore-Anderson, 2021b: 13). Unfortunately, typical biology assessments seen in schools that utilise short-answer questions do not provide the opportunity for students to demonstrate this broader understanding of biological systems, or their capability to integrate biological knowledge.

Crucially, McTighe and Curtis (2019: 81) stress that '*we measure what we value*', and '*what gets measured is what gets done*'. Without inclusion of assessment tools that measure understanding beyond short-answer questions, there will be little incentive to shape pedagogy (for the teacher) and learning (for the student) to foster what Darwin famously referred to as longer trains of thought (Gruber, 1981).

The purpose of this article, hence, is to present adapted versions of my two frameworks (Moore-Anderson, 2021a; 2021b) that can be used for assessment, performance reporting, and helping students understand how to learn within biology. Rubrics have long been a classroom tool that share success criteria with students, yet they are often complex and context specific. The frameworks presented here are simple enough for both ease of comprehension and generalisability across biological contexts and educational stages. They are not intended to replace other assessment methods but to complement them. I shall explain them in turn and if readers are interested, they are encouraged to read the original articles where they can find the full depth of rationale behind their creation.

The first framework (adapted from Moore-Anderson, 2021a) focuses on biological systems understanding and the importance of students developing a connected understanding of the underlying causes of phenomena in systems. The wording has been highly modified to provide a framework that is easily accessible for both students and teachers, and to be generalisable across educational contexts. My second framework (adapted and modified from Moore-Anderson, 2021b) focuses on integrating what can be seen as separate facets of biology: physiology and development, with ecology and evolution. An explanation of the framework and an example are provided for both.

Framework 1: Assessing and fostering students' biological systems understanding

The first framework (Figure 1) helps students distinguish between two important aspects of their learning:

- The connectedness, which can be considered the difference between rote learning (isolated memorisation) and meaningful learning (connected knowledge).
- The quality of knowledge, which refers to how useful the knowledge is to the student for explaining phenomena. In this framework, it is the difference between knowing an overview of a system's entities and their functions, and knowing the underlying causal processes that explain observations of a system.

While the framework is organised into quadrants, the two axes are continuous.

When understanding is centred around description of what there is and their functions, it is useful, but limited. Knowledge of the underlying causal mechanism is more useful as it allows thinking about how the system works. Nevertheless, it is the conjunction of both mechanistic and connected (not rote) knowledge that empowers students with flexible understanding. By understanding the underlying causal processes, students can rationalise how changes to the system affect its outputs.

Below I explore this idea with a concrete example for ages 14-plus, and what I would expect students to talk about for each quadrant.

Example question

Tell me about the heart and what would happen if there were a hole in the septum between the ventricles.

Novice knowledge

Novice students might recall the names and position of some components of the heart, especially the most salient, such as the atria and ventricles. They may mention

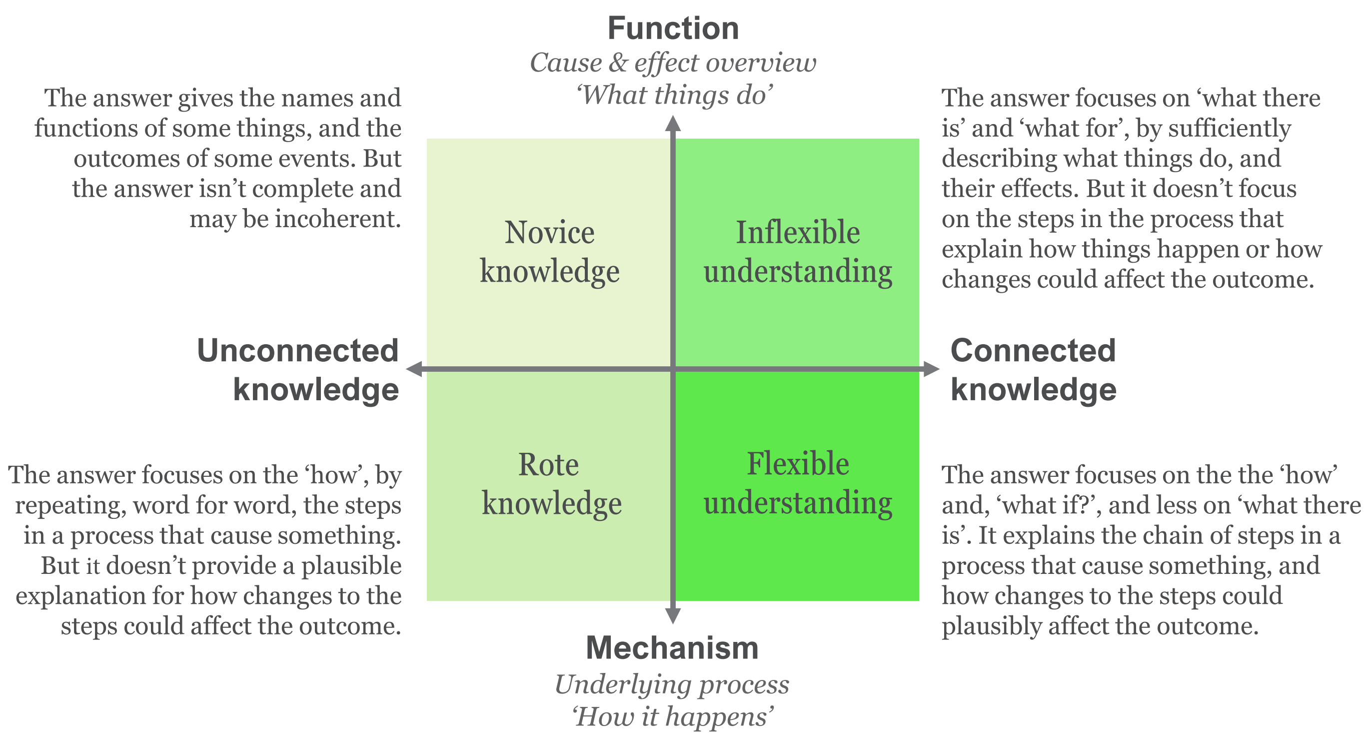

Figure 1 The assessment framework for biological systems understanding with an explanation of the meaning of the quadrants, adapted from Moore-Anderson (2021a)

some functions, such as '*the ventricles pump blood out of the heart*', but these may not be related to the working of associated structures, or their role in the whole organism. This may give an incomplete feeling to the answer. As these knowledge structures are not very meaningful for the student, typically memorised verbatim, the answer may state names and functions incorrectly interchanged.

Inflexible understanding

This student's answer is similar to the above (novice knowledge) in that it focuses more on the names and functions of the heart's components. The answer may give the notion of a list, even if it is in the correct order of the cardiac cycle, as it generally lacks reference to the underlying step-by-step causality of a mechanism that links the components. For example, a concise student answer may read: '*The atria pump blood into the ventricles. The ventricles pump blood out of the heart, and the valves prevent backflow. The arteries take blood away from the heart*.' The lack of explicit mechanistic reasoning and the lack of a coherent answer to the 'what if?' question is what differentiates this answer from flexible understanding.

However, the answer does give an overview of the heart and its general function, which gives the student an understanding of its role in the larger organism system. This point is important, as it distinguishes it from novice knowledge. The student connects the heart to the organism and the organismal systems in a coherent manner. I would expect the student to situate the components of the heart correctly, but also mention their role in the organism.

Rote knowledge

Students who focus on rote knowledge in their answers differ from both novice knowledge, and inflexible understanding in that they are usually coherent, following the cardiac cycle in order and denoting the mechanism by which the heart functions. Mechanistic reasoning includes considering the spatial relationships between components, and how one step in a process causally leads to another (Russ *et al.*, 2008). For example, rather than simply stating that a chamber pumps blood, the answer could refer to how the contraction of muscle leads to an increase in blood pressure that causes blood to flow. Likewise, rather than simply stating that valves prevent backflow, a mechanistic response may refer to how valves are closed by the pressure of the blood, so preventing passage of the blood.

Nevertheless, because such students have memorised most of their answers verbatim, they lack meaning to the student. This is observed in answers that incorrectly interchange components and functions, or steps in the process, and those that don't mention how the process relates to the whole organism. A highly coherent rote knowledge answer can be differentiated from flexible understanding by its lack of explanation of what would happen if there were a hole in the septum, or, if this were attempted, the explanation would be incoherent.

Flexible understanding

We are able to observe performance of flexible understanding by including a 'what if?' clause in the question. The answer is similar to rote knowledge in that it focuses on mechanism. It is similar to inflexible understanding in that it holds meaning to the student, which is shown in the answer through how the student connects their knowledge. Yet, the answer differs from all other quadrants because it coherently answers the 'what if?' question, showing flexibility in thinking.

In this section of the answer, I would expect students to refer to blood pressure and its causes. They would distinguish between the ability of the left and right ventricles' muscle mass, the blood pressure they cause, and thus the consequential flow of blood from the left ventricle to the right ventricle. I would expect the student to attempt, but not necessarily perfectly deduce, an explanation of the consequences of this on the heart, blood flow through it, and the flow of oxygenated blood in the circulatory system. Of course, these expectations will depend on the educational stage of the students.

An additional feature of answers showing flexible understanding is the focus on what is happening, rather than what there is. Hence, an answer from a student with highly meaningful mechanistic knowledge may also be more abstract, referring more to system processes than component parts. For example, a student may refer to the mammalian heart '*as a pump with four chambers, two of which function to pump blood under high pressure around the body (called the ventricles), and two of which function to receive and fill the ventricles with blood*.'

This flexible understanding is also known as systems thinking, which the US National Research Council (2010: 63) defines as: '*the ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a 'big picture' perspective on work*'. This is important in developing biological thinking as it helps students to draw together what happens across levels of organisation from cell through organ and organism, as well as through lenses of ecological and evolutionary success. The current literature on systems thinking in biology shows that students generally struggle to trace matter across levels of organisation in physiological and ecological systems (Moore-Anderson, 2021a), which suggests that students need explicit guidance, and practice in connecting the phenomena they learn in biology courses.

In my first article (Moore-Anderson, 2021a), I summarise the literature on systems thinking in biology education, which indicates how students without guidance incline towards the learning of entities and their functions, and how they need explicit guidance in focusing on the causal mechanisms of systems. Equally, experts are much more likely to include mechanisms in their explanations compared with novices who focus more on functions. In my personal experience, this function–mechanism distinction, when shared explicitly with students, helps empower them to understand what good learning in biology looks like.

Assessments that focus on short-answer questions are more likely to measure either rote knowledge or inflexible understanding. A major cause of this is probably the limited scope of the question for the elaboration required to exhibit flexible understanding. While short-answer forms of assessments provide ease of standardisation, I recommend including some assessment with biology students that requires extended and open writing, using this framework. A question is required that allows for answers that can be assigned to any of the four quadrants in the framework (novice knowledge, rote knowledge, inflexible understanding and flexible understanding).

A model that has worked in my classroom is to ask the question in this format: '*Tell me about X, and what would happen if Y*'. Initially, students may try to answer this as two separate questions, attempting to write everything they know for the first section. However, with guidance, examples and time or space restrictions, their focus should improve on choosing what they consider to be the most important information to discuss. Other examples that might work are:

- *Tell me about the human digestive system, and what would happen if the stomach had to be removed and the oesophagus was joined to the intestine.*
- *Tell me about population dynamics in this marine food chain, and what may happen if fishing of X was banned.*

Curricular use of the framework

Following McTighe and Curtis's I-O-I model (2019), it is important that evidence of student performance is recorded for three reasons. Firstly, the qualitative nature of the frameworks allows assessment to focus on the quality of learning rather than numerical grades. Secondly, it informs on the success of the correspondence between the chosen pedagogy and the desired impact on the students. Thirdly, by recording this evidence and using it in the reporting of student progress, it gives it equal status to the other types of data that are obtained (e.g. quizzes, end-of-term exams). This then provides the incentive to shape the curriculum and classroom pedagogy around these goals. Of course, before being able to perform at the level of flexible understanding, students will require practice. Following the backward design stipulated by McTighe and Curtis (2019), it would be beneficial to plan the 'what if?' questions that should be reserved for assessing answers more formally using this framework, and then for those to be used during teaching. Teachers may choose to use the framework for assessment once per term, once per topic or more frequently, depending on the course, the range of student capabilities and time constraints. I also believe it would be beneficial to share the framework as much as possible with students to promote their own metacognition and help develop self-regulated learners.

Framework 2: Assessing and fostering students' capability for integrated thinking

The second framework (Figure 2) is a modified version of my framework for curricular design (Moore-Anderson, 2021b), the purpose of which was for biology curricular design to integrate more explicitly and frequently the different facets of biology: physiology and development with ecology and evolution. For example, when students study the human heart and the circulatory system in isolation, it can seem like a course on how your body works. By integrating physiology and development with ecology and evolution, students will form a better understanding of patterns in nature. By integrating the encompassing concepts of evolution and the organism in its environment, students are provided with frameworks for finding meaning in the new content they learn. Ultimately, however, a principal goal of the use of the framework is to foster the disposition of seeing like a biologist: '*Indeed, when students leave the classroom, whether in an urban or rural environment, they generally see whole organisms* [such as plants, birds, and insects], *and the questions they pose should pertain to the lives of the organism, how it lives, how it is able to survive, how it reproduces, and why it is the way it is*' (Moore-Anderson, 2021b: 3).

The curriculum should encourage students to look around them, observe nature and reflect upon it. Are students able to actively transfer their knowledge to these observations, such as pondering how physiological systems affect the organism's autecology, or indeed why it evolved? This capability for integrated biology thinking and inquiring is important, but it is not readily observable in the short-answer questions. Thus, as with the previous framework, space must be made for extended student cogitation and writing.

Following the I-O-I model of McTighe and Curtis (2019), the desired impact of the course, in this case, is the capability to think in an integrated manner. The

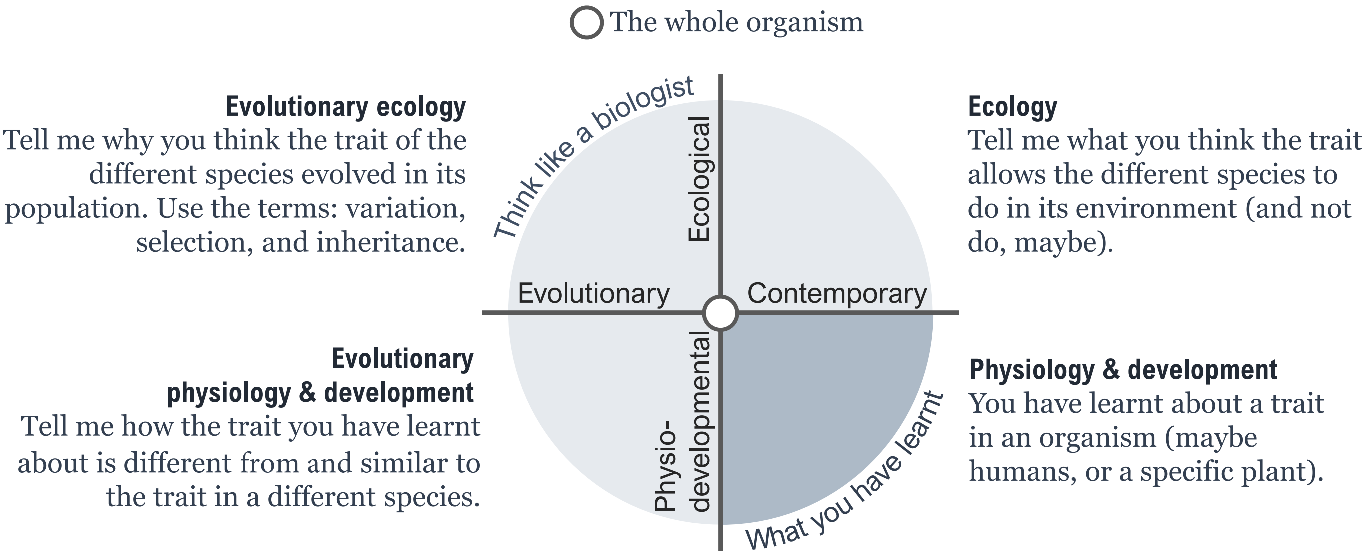

Figure 2 The assessment framework for integrated understanding with an explanation of the meaning of the quadrants, adapted from Moore-Anderson (2021b)

following step is to consider what evidence of student performance could be obtained to ascertain the effectiveness of the pedagogy for the defined goal. The framework for integration (Moore-Anderson, 2021b) has been modified (Figure 2) to one that can be used by the teacher for assessment and shared with students to foster their understanding of learning in biology.

Unlike the first framework (for biological understanding), which categorises answers into one of the four quadrants, this framework is designed to represent, in simple terms, the capability to integrate the different facets (and thus quadrants) of the whole organism. For assessment, a question is required that provides enough scope for students to show their thinking in each quadrant. I recommend this format:

You have learnt about X (a trait) in species 1. Using this knowledge:

- *Compare X (a trait) in species 1 with Y in species 2.*
- *Tell me what you think Y allows species 2 to do in its environment.*
- *Tell me why you think Y may have evolved in species 2's population, using the terms 'variation', 'selection' and 'inheritance'.*

The addition of comparative biology allows us to observe pattern recognition in students across different contexts, and the comparison point should help students to answer the questions about ecology and evolution. It would be necessary for either, or both, an annotated graphic and a short text with a description of the trait in species 2 to be shared with the students.

Below I give a concrete example of a text, a question and the possible answers that would indicate thinking in each quadrant.

Example text

Bats are small mammals that can fly using wings that are formed from living skin spread between elongated fingers and the body. Bats are generally of two groups: those that are larger and eat fruits, and those that are smaller and hunt flying insects or fly to locate flower nectar. Most bats are very proficient fliers and more agile than most birds but flying is costly in terms of energy. Like all mammals, bats have lungs for gas exchange. However, they can also carry out around 10% of their gas exchange through their wings. While these wings are made of skin, it is different from their other body skin. Their body skin is thicker (around 60 μm), with hair, sweat glands and a fat layer. The wing skin is thin (around 10 μm), has lots of blood vessels, and no hair follicles or fat layer. (Makanya and Mortola, 2007)

Example question

You have learnt about gas exchange in human lungs. Using this knowledge:

- *Compare gas exchange in bat wings with gas exchange in human lungs.*
- *Tell me about what you think gas exchange in wings allows bats to do in their environment.*
- *Tell me why you think gas exchange in wings has evolved in the bat population, using the terms 'variation', 'selection' and 'inheritance'.*

Expected answers

Evolutionary physiology

Tell me how the trait you have learnt about is different from and similar to the trait in a different organism.

Depending on the educational stage, I would expect students to observe the general similarities found in exchange surfaces: short diffusion distance, highly vascular, and large surface area. For the differences, students could refer to the external and exposed nature of wings compared with lungs and the difference in the method of maintaining a concentration gradient: breathing compared with movement of wings through air.

Ecology

Tell me what you think the trait allows the different organism to do in its environment (and not do, maybe)?

Students could refer to the high energy cost of flying and the need for a rapid supply of oxygen to the bat's muscles, or the necessity for excretion of large quantities of carbon dioxide. The extra oxygen supply could be especially useful in bats that hunt insects, which require fast, agile flying. Students could also explore a trade-off, such as the idea that the highly vascular wings could make temperature homeostasis more difficult if it is cold.

Evolutionary ecology

Tell me why you think the trait of the different organism evolved in its population. Use the terms: variation, selection and inheritance.

An important problem for the students is to identify the appropriate trait to discuss. I would expect students to identify the wings as gas-exchange surfaces, but they could discuss more deeply that there are several components to this, such as vascularity, and the development of a thin wing. I would want students to then express that there would be variation of this trait in the population. Then, I would want students to identify the selection pressure that has acted on this trait for it to be in its current form. In this case I would expect students to refer to flying ability, which directly affects hunting ability, or food location ability, and thus the energy intake of the bats. Finally, I would expect students to discuss how individuals with the selective advantage are more likely to survive, reproduce and transmit their genetic material.

Ideas for more questions

- Comparing the mammalian four-chambered heart with the two-chambered heart of fish.
- Comparing the digestive tracts of mammals with that of a hydra.
- Comparing the gas-exchange systems of mammals and birds.
- Comparing C4 plants with CAM plants
- Comparing a temperate plant's stomatal anatomy with a xerophyte such as *Nerium oleander*, which has stomata in pits with trichomes.

Curricular use of the framework

Like the first framework (for biological systems for understanding), assessment should only come after classroom practice and I recommend planning into the curriculum the examples that can be used in teaching, and those that are appropriate for assessing.

Unlike the first framework, the second one is likely to be used for assessment less frequently as it requires extensive reflection on several different facets of biology and the creation of a good example for comparison. I would recommend its use at least termly, although teachers may find it useful at the end of any physiology or development topic, depending on their goals.

As mentioned above, I recommend recording evidence of our students' capability to integrate their learning after using this framework for assessment. The data should be recorded separately for each student so that teachers can assess the effectiveness of their pedagogy in developing the different capabilities. For example, students may prove to be well versed in looking for patterns in different species, but may not yet be thinking, as a habit, about why such systems have evolved.

Feedback

There has been increased attention on the value and effectiveness of marking and feedback in recent years (e.g. Education Endowment Foundation, 2021). One issue with book marking is that book work is often used as a sketch pad for external thought processes, or simply to record and correct answers to questions. The generalised use of the frameworks presented in this article allows the teacher to observe, communicate and record something more meaningful. To avoid increasing already-heavy workloads, feedback does not have to be the annotation of the work by the teacher; recording of the data can be done through a quick read, expert judgement, and a best-fit strategy. Equally, feedback to students can be through self-assessment, and whole-class feedback with teacher-selected examples. The latter could be particularly fruitful if students are accustomed to the frameworks and the teacher asks students to compare examples before explaining why they represent the specific quadrants of the frameworks (Siegler, 1995; 2002). It is the communication and discussion that will support students in acquiring a broader and more connected approach to biological thinking.

Conclusion

With consistent use of the frameworks, not just in assessment but as part of everyday learning, it is more likely that students will develop a better understanding of learning itself. While standardised testing has its place in biology education, this currently favours short-answer questions as evidence of biological knowledge and understanding. Providing feedback on these answers can be difficult, as in many contexts it is restricted to telling the student what they need to learn or relearn. The frameworks presented in this article offer the opportunity for students and teachers to participate in more fruitful conversations about a student's improvement in biological thinking. Ultimately, students may themselves be empowered to generate their own learning and biological understanding, towards goals that exist beyond the answering of short-answer exam questions.

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How does COVID-19 spread? A 5E activity to address argumentation and the nature of science

Rola Khishfe

Abstract The article describes a science activity designed to increase students' knowledge and awareness of the spread of COVID-19. It helps students achieve scientific literacy through improving their views about the nature of science and their argumentation skills. It also promotes students' engagement in scientific practices such as modelling, collecting data, analysing it, and representing it in tables and graphs. The activity aims to simulate the spread of any infectious disease. It adopts the 5E approach, which is integrated into the context of inquiry, argumentation and nature of science. Integration of science and mathematics is also an added value of the activity.

The many changes that people have witnessed in the healthcare recommendations regarding the 2020 COVID-19 outbreak have probably led to a declining trust in science among the general public. The general public's views on social media reveal a gap in people's understanding of the nature of science (NOS) and mathematical modelling, as well as how these two elements contribute to recommendations about COVID-19 (Bloom and Fuentes, 2020). Curricula should provide students with opportunities to understand NOS (National Research Council, 1996) and mathematical modelling (National Research Council, 2013). These views also reveal a gap in school science curricula with regard to these scientific concepts.

The science activity described here is an opportunity to increase students' knowledge and awareness of the current worldwide health crisis, that is, the spread of COVID-19. It helps students achieve scientific literacy through improving their views about NOS and their argumentation skills. It also promotes students' engagement in scientific practices such as modelling, collecting data, analysing it, and representing it in tables and graphs.

The activity is based on a lab activity designed by Jennifer Doherty and Ingrid Waldron (2009) that aims to simulate the spread of any infectious disease. However, the present activity goes beyond the previous one in the adoption of the 5E approach, in which the activity is integrated into the context of inquiry, argumentation and the nature of science. Integration of science and mathematics is also an added value of the activity, as well as the connection to a currently lived phenomenon – the spread of COVID-19.

During a recent research project, we had the opportunity to teach this activity to 25 grade 9 students (ages 13–15) in a school in Beirut (Lebanon). The teaching time required was 120–150 minutes. This activity requires that teachers have good knowledge about the virus, its origin, exponential way of spreading, testing, predicting the number of infected individuals, and methods of protection. We suggest that teachers research reliable sources such as the World Health Organization (see *Weblinks*) to collect the required information and be prepared for the possible questions about the virus that students may pose during their discussions.

Objectives of the activity

By the end of this activity, students will have demonstrated their ability to:

- model the spread of the virus that causes COVID-19 using water and baking powder;
- collect and analyse data;
- compare data and data analyses to look for a pattern/mathematical relationship;
- visually represent data in tables and graphs;
- work collaboratively to generate the different parts of an argument;
- explain that scientific knowledge is tentative, empirical and inferential (relating to NOS aspects).

Focus questions (scientific inquiry)

- What is COVID-19? How does it spread?
- Do you think that our adopted model represents the virus spread phenomenon accurately? How does it resemble the studied phenomenon? How does it differ from it?
- Can you, as an epidemiologist, predict the number of infected people? How can you justify your claim?
- How can you, as an epidemiologist, trace the infected cases to the primary source of infection?
- Do you think that what we know now about COVID-19 may change in the future? Justify your answer.

Materials

For the *Explore* phase, the following are needed:

- small paper cups (1 cup per student)
- baking soda (sodium bicarbonate)
- phenolphthalein pH indicator
- small transparent bottle with an eyedropper for phenolphthalein
- 1 dm^3 bottle/beaker for mixing the basic solution
- tap water

For the *Elaborate* phase, students need the same materials as used in the *Explore* phase, but each student should also be given a new cup and the *Handout* (Box 1)

5E instructional model

The 5E model (Bybee and Landes, 1990) is an instructional model that the Biological Sciences Curriculum Study began using in most of its programmes in the late 1980s. It provides a carefully planned sequence of instruction that puts students at the centre of learning. The model consists of the following phases: *Engage*, *Explore*, *Explain*, *Elaborate* and *Evaluate*. Each phase has a specific function and contributes to the overall coherent instruction.

Engage phase

Big question: What do you know about COVID-19?
We started the session by engaging students in some questions about the phenomenon of COVID-19 spread, such as:

> *What is an infectious disease? Is it dangerous? Why? Do you know an example of an infectious disease?*

Once students mention COVID-19, we asked them to share what they have heard about it: its origin, its effects on the human body, why it is considered an infectious disease, how they protect themselves, and most importantly, how it spreads.

Explore phase

Big question: How does COVID-19 spread?
In this phase, students explored the phenomenon, 'The spread of the virus that causes COVID-19' as epidemiologists. They practised modelling the virus spread using water and sodium bicarbonate, using the following steps:

1. *Preparation of the infected solution:* We mixed 60 g of sodium bicarbonate with 500 cm^3 of water in the beaker.
2. *Preparation of students' materials:* We prepared one cup for each student. A quarter fill one of the cups with the infected solution. Quarter fill all other cups with tap water. It needs to be noted that only one student in the class has a quarter-filled cup of sodium bicarbonate (sodium hydrogen carbonate) solution.
3. We divided students into pairs.
4. We explained the activity to the students. We told them that each one of them would receive a cup containing a clear solution. All the cups contain tap water and only one cup contains an aqueous solution of sodium bicarbonate. When each pair of students receives their cups, one of them pours the content of the cup into their partner's cup. Then, the partner pours back half the amount into the emptied cup. We told the students that this would be referred to as the 'first round'. In the 'second round', students move in the classroom to choose any other student and repeat the same procedure. Then, students return to their seats and add a few drops of a colour indicator to find out which students have mixed their solution with the aqueous solution of sodium bicarbonate. Only those who mixed their solution with the sodium bicarbonate solution will see the colour of their solution change.
5. After this explanation, we asked students how this experiment relates to the discussion about COVID-19. Also, we asked them how the adopted model resembles the studied phenomenon and how it differs from it. We made sure they understood the model before following the procedure explained in step 4.
6. We followed the procedure explained in step 4, but before adding the indicator, we had students work in groups, for around 15 minutes, to predict the number of infected individuals. We asked each group to present its argument to the class. We provided support, whenever needed, to help them describe the parts of their arguments (claim, evidence and reasoning). When all groups had presented their arguments, we told them that we were going to use an indicator (phenolphthalein) that models the test for the virus. When 2 or 3 drops of the indicator are added, the infected solutions would change colour. Thus, if a student interacted (exchanged solutions) with the primarily infected person in the class or someone who had come into contact with the infected person, they were now infected and their solution would turn red. On the other hand, if they did not interact with any infected individual, then the colour of their solution would not change (it would remain colourless). The students showed the colour of the solutions to the class, so that they could count the number of infected individuals, and decide whether their claim was correct.
7. We disposed of the solutions into the sink and rinsed it with water.

Box 1 Handout

Part A: Argument organiser

Big question:	
Evidence (What are the specific observations or data that support your claim?)	**Reasoning** (How does this evidence support your claim? What is the scientific principle or theory that explains why this evidence is linked to the claim?)
Your claim (What is your answer to the big question?)	
Write a paragraph that explains your answer to the big question and use your evidence and reasoning.	

Part B: Answer the following questions

- Give an example of an observation you have made in this activity.
- Give an example of an inference you have made in this activity.
- How were you able to reach your claim in this activity?
- Do you think you might change your claim? Why?

Teacher tip

Scientists develop and employ models to understand natural phenomena and formulate theories. All scientific practices are interrelated, but modelling is believed to drive the deployment of the other scientific practices advocated by the K–12 Science Education Framework (Lehrer and Schauble, 2015). Modelling includes analogical mapping to a familiar setting, representations such as tables and graphs, and materialising natural systems for a better understanding of the world around us (Lehrer and Schauble, 2015).

In this activity, students had to realise that the virus is modelled by a chemical (sodium bicarbonate), the fluids of the human body by a cup of water, and the virus test by a pH indicator. They also visually represented data in tables and graphs. As a result, they came to the conclusion that modelling, in this activity, allowed them to understand how a contagious virus spreads.

Safety first

Safety is of course very important in any science lab or classroom, especially when studying infectious diseases. In such activities, it is safer to study a model rather than the real virus. As a safety measure, students were warned not to attempt to drink the liquid because they might be working with the solution that has the chemical.

Explain phase

Big Question: How can the number of infected individuals be determined?

We asked the students to explain their results from the *Explore* phase. We scaffolded them to complete this table:

Number of rounds	0	1	2	3
Number of infected individuals				

Figure 1 shows how the number of infected individuals increases.

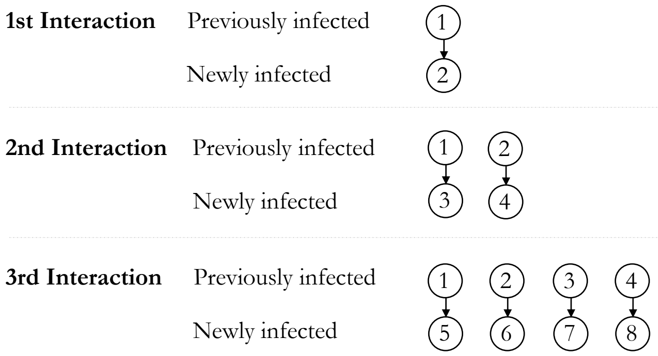

Figure 1 Increase in number of infected individuals with each interaction

We then asked them to identify a mathematical pattern in the number of infected individuals with respect to the number of interactions. They noticed that the number of infected individuals doubled after each round. We guided them to reach the following mathematical relationship:

Number of infected individuals = $2n$

. . . where n represents the number of rounds.

We asked students to draw a graph to represent the tabulated data. Then, we asked them to extend the graph by plotting the point corresponding to a fourth round of interactions using the above mathematical relationship.

Elaborate phase

Big question: Who is the primary source of the infection?

In this phase, students acted as epidemiologists to identify the primary source of infection. Their argumentation resembled scientists' argumentations towards reaching a consensus, if any. Before the activity began, we told them that they were supposed to have the skills and values of scientific inquiry, that is, logical thinking, precision, open-mindedness, objectivity, scepticism, replicability of results, and honest and ethical reporting of findings.

1. We repeated steps 1–4 from the *Explore* phase and got students to record on the board the names of the students with whom they interacted as indicated in this table.

Student's name	Who did you interact with?	
	1st round	2nd round

2. Students inquired about the primary source of infection. We distributed the *Handout* (Box 1) and asked them complete it. This step took about 20 minutes.
3. Students shared their answers in a class discussion.
4. During the discussion, we took the opportunity to remind students of some protocols for reducing the spread of the virus, such as avoiding contact with people who are sick, staying home when they are sick and washing their hands often with soap and water.

Evaluate phase

Pre-assessment

The prompt '*share what you have heard about COVID-19*' was given as a discussion task to assess students' prior knowledge. Preliminary assessment of students' NOS views and argumentation skills required further questions, such as '*Do you think that what you know/what doctors are saying now about COVID-19 may change in the future? Justify.*'

Post-assessment

We collected the *Handouts* to assess students' argumentation skills and NOS views. The *Supplementary Assessment* (Box 2), which includes another possible evaluative measure, was also administered to students at the end of the activity.

Argumentation skills

The assessment of argumentation was done using the following rubric:

- **Naïve.** The response was given a *naïve* categorisation when the student did not provide any claim or the claim was unsupported by evidence. For example, if a student gave the response that '*Student X is the source of infection*', that response would be categorised as naïve, as the participant did not provide any evidence for their claim.
- **Intermediary.** *An intermediary* categorisation was given when a participant's claim was supported by one piece of evidence only and/or valid reasoning was not provided to connect the evidence and the claim. For example, a student response that '*Student X is the source of infection because there was a change of colour when we*

Box 2 Supplementary Assessment – COVID-19: Lockdown versus herd immunity

With the declaration that COVID-19 was a pandemic disease, countries all over the world began to appraise possible approaches to mitigate its severity. In the absence of a vaccine, some scientists advocated imposing a national lockdown, while others called for allowing herd immunity to build.

Those who were in support of lockdown argued that this approach would decrease the average number of people infected by each infected individual. When fewer individuals are infected, the chain of transmission is broken and the number of cases at the hospitals decreases. A study conducted in August 2020 showed that lockdown is an effective way to reduce the rate and extent of infections. Nevertheless, despite much media debate and research about which measures are better, lockdown or herd immunity, there is a lack of definitive data on the effectiveness of lockdown measures.

Those who supported the herd immunity approach argued that lockdown until a vaccine was developed could have a devastating effect on physical and mental health, as well as social and economic life. They believed that individuals in a population (herd) should pursue their regular lives and contract the virus, because it is only through contracting the virus that they could develop natural population immunity (herd immunity). Then, when a large percentage of the population becomes immune to a disease, the spread of that disease slows down or even stops. Herd immunity has proved somewhat effective in some countries, such as Sweden. Some argued that attempts to reach 'herd immunity' through intentionally exposing people to the virus were scientifically problematic and unethical. Allowing the free spread of the virus could cause deadly infections, especially in those with low immunity, the young and the elderly.

(Text adapted from: www.who.int/news-room/q-a-detail/herd-immunity-lockdowns-and-covid-19 and www.news-medical.net/news/20200817/COVID-19-Englands-lockdown-vs-Swedens-herd-immunity.aspx.)

1 Which approach of protection did your country adopt?
2 Do you think that the approach adopted by your country was effective? YES NO
3 Explain and justify your answer.
4 If you were a scientist who had the authority to impose a particular approach to mitigate the severity of COVID-19, which approach (lockdown or herd immunity) would you choose?
5 Explain and justify your decision.
6 Another scientist in your country, Professor Loren, disagrees with your decision. How could she explain her position to illustrate the reasons supporting it and convince you?
7 What would you reply to Professor Loren to explain that your decision is right?
8 Do you think the scientists are certain (sure) about the knowledge they have about COVID-19? Explain what makes them certain or uncertain.
9 Do you think you might change your decision in the future? Explain why or why not.

poured from his cup' was categorised as intermediary because the claim was supported by one piece of evidence and they were connected by valid reasoning.

- **Informed.** A response was categorised as *informed* when the student gave a claim that was supported by more than one piece of evidence, and the claim and evidence were connected by valid reasoning. For example, a student gave the response that '*The solution of Student 1 was infected when there was an interaction with Student 3. Student 2 was also infected when there was an interaction with Student 3. So Student 3 is the source of infection because there was a change of colour in both cases*.' The response was considered informed because the student exhibited a claim that was supported by two pieces of evidence and they were connected by valid reasoning.

After the responses about argumentation were categorised the following points were given: 1 point for naïve; 2 points for intermediary; 3 points for informed.

Nature of science views

The assessment of NOS views was done according to the following rubric used in previous studies (Khishfe, 2008; 2012):

- **Naïve.** A category of *naïve* was given when the student's response did not exhibit the accepted views of science educators about the aspect of NOS. For example, the student's understanding of the tentative aspect of NOS was considered naïve when they responded that '*Scientists are certain about the knowledge they have about COVID-19 because this scientific knowledge is proven*'.
- **Intermediary.** A category of *intermediary* was given when the student's response involved multiple co-existing views that contradicted each other. For example, their understanding of the tentative aspect of NOS was considered intermediary when they explained that '*Scientists are not certain about the knowledge they have about COVID-19*' and then mentioned that '*the knowledge that we have about COVID-19 is true because it is proven*'. These two ideas contradicted each other.
- **Informed.** A category of *informed* was given when the student's response exhibited the views accepted by science educators about that aspect of NOS. For example, their understanding of the tentative aspect was considered informed when they responded that '*scientists are certain about the knowledge they have about COVID-19 because this is the best knowledge they have reached so far based on the available evidence*'.

After the responses about NOS aspects were categorised, the following points were given: 1 point for naïve; 2 points for intermediary; 3 points for informed.

Summary of results

The results show that many students exhibited more informed argumentation and NOS understanding by the end of the activity, which offers compelling evidence that high-school students can improve their understanding of NOS and their argumentation skills by engaging in this activity. For example, students related the big question to the primary source of infection. To support their claims, they linked to specific observations or data: '*There was a change in colour when we exchanged with Student X but there was no change in colour when we exchanged with Student Y*.' When asked to explain their reasoning, they referred to the table with the names of students they had interacted with. For NOS, students referred to observations of the interactions they had with other students (whether there was a change in colour or not). Regarding inferences, students referred to the student or students who were the source of the infection. At that point, students said they reached their claim about the primary source of infection based on the data they had collected. Some of them noted that they might change their claim depending on the data and any new evidence encountered.

Conclusion

Helping students develop argumentation skills and understand NOS favours the achievement of scientific literacy (National Research Council, 1996).

Argumentation

Teaching argumentation is vital in science education because it triggers students to construct scientific knowledge, develop critical thinking, and achieve scientific literacy in terms of communicating science as well as developing epistemic knowledge and reasoning (Jimenez-Aleixandre and Erduran, 2008). This activity provides students with multiple opportunities to practise argumentation through developing claims (assertions), supporting them with evidence (observed or analysed data), reasoning (a justification of the claim based on the evidence), and refining their claims based on class-pooled evidence.

Nature of science

According to the K–12 consensus view of NOS, students should be given opportunities to develop informed views about scientific knowledge (Abd-El-Khalick, Bell and Lederman, 1998). This activity mainly targets three aspects of scientific knowledge:

- **Scientific knowledge is based on evidence:** Students are expected to develop this view in their search for evidence that supports their claims.
- **Scientific knowledge is tentative:** Students could be scaffolded to realise this aspect in the *Engage* phase by bringing to the fore the fact that knowledge about the virus (e.g. symptoms, ways of spread, and possible vaccination) has undergone several changes since its first appearance.
- **Scientific knowledge can be observed and inferred:** Students are expected to observe (gather data using the five senses) and infer (make a guess based on the observations) throughout the whole activity. The distinction between inferences and observations should be made explicit by the teacher.

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The virtues of inspirational teachers: a hierarchical model

Stephen Rowcliffe

Abstract Inspirational teaching is a fairly well-researched field, and the benefits that it brings to student learning are manifold. Although the characteristics of inspirational teaching practice have been studied, there is no clear, universally recognised framework for understanding them. This article presents the results of a literature review, in conjunction with some primary research into the benefits and characteristics of inspirational teaching, and includes a hierarchical model developed to summarise and conceptualise its main features.

Several studies (Jensen, 2013; Bradley, Kirby and Madriaga, 2015; Blaylock *et al.*, 2016) have concluded that students are more motivated to complete their schoolwork when inspired by their teacher, and that their minds are more open to new experiences and new knowledge. Inspirational teaching is more enjoyable, both for the learner and the teacher; is known to have long-lasting positive effects on students' aspirations, interests, self-confidence and self-concepts; and is positively associated with increased levels of creative thinking. Inspirational teaching is flexible and fluid, adapting to the interests and questions of the learners, seldom remaining shackled to lesson plans or curricula, and possibly as a result of this, rather rare in schools in the 21st century (Lamb and Wedell, 2013).

The advent of the internet and its myriad applications and benefits for education over the past few decades, accentuated during the recent COVID-19 pandemic and associated increase in home-based learning, have led to a frame-shift in perceptions of the role of teachers in education. Now, children can watch online video tutorials and access learning resources, specifications and textbooks, answering almost any question they have, independently of their teacher. A world of knowledge literally lies at their fingertips, and thus the teacher is no longer the custodian of knowledge that they once were.

Moreover, the changing landscape of work that the information age is heralding may lead some students to question the value of what schools and teachers have to offer them, especially if teaching is impersonal and didactic, and curricula outmoded, inflexible and irrelevant. Indeed, recent surveys of dissatisfied students in higher education have revealed a desire for greater passion, dynamism and ability to establish rapport from their lecturers (Heffernan *et al.*, 2010; Bradley *et al.*, 2015). As such, inspirational approaches to teaching may be among the last things that teachers are in a unique position to offer their students, if lessons and content can just as easily be 'delivered' online.

Roosevelt and Garrison (2018) decry the extent to which the narrow focus of modern US practice-based teacher education, with its overbearing emphasis on skills assessment, has robbed teachers of the intellectual curiosity, independence and 'soulfulness' that they require to inspire their students. They cite a lack of recognition of inspirational teaching as a key factor in the teacher retention crisis. O'Connor (2008: 117) laments the fact that:

> *although emotions are at the epicentre of teachers' work, the intangible emotional and empathic qualities which make a 'good teacher' from the viewpoint of the students cannot be measured and are thus considered worthless by policymakers.*

Whereas the UK Department for Education (DfE) recognises the importance of inspirational teaching practice, stating that teachers should '*inspire, motivate, and challenge pupils*' (DfE, 2011: 10), and reports by the Office for Standards in Education (Ofsted), the UK's national school inspection agency, regularly use the words 'inspiring' or 'inspirational' to characterise outstanding teaching (Sammons *et al.*, 2016), there is little official guidance as to how teachers may achieve these goals in school settings, or even what the specific characteristics of inspirational teaching might be.

Teacher virtues

The closest *Oxford English Dictionary* definition of what is meant by 'virtue' in this context is '*a particular good quality or habit*' and has nothing to do with morality (although teachers must of course also be held to high moral standards). The reason that the concept of virtues was considered useful in this analysis is based on the ideas of Aristotle, who regarded virtues as dispositions of character, formed through the habitual practice of 'doing the right thing'. Virtues are elements of an individual's personality, and unlike skills, which can be taught, they require an element of wisdom, gleaned from experience.

In a study of many different, diverse ethnic groups, Annas (2004) found the concept of virtues to be almost universal, and an effective inter-cultural language, and although critics of a virtues-based approach complain that there are no absolute rules or guidelines on how to act, this may in fact be a strength of the virtues approach, as each teacher is free to express the virtues in their own way.

The concept of 'teacher virtues' is far from new. Huttunen and Kakkori (2007) discuss how Aristotle's 'Nicomachean Ethics' from the 4th century BC logically leads to a concept of pedagogical friendship between teacher and student, separate from any deontological or Kantian duty that a teacher has to care for those in their charge. Merriman (2020) highlights the work of John Baptist de La Salle in the 17th century, a pioneer in teacher education, who emphasised the importance of 12 teacher virtues: seriousness (gravity), silence, humility, prudence, wisdom, patience, reserve (restraint), gentleness, zeal, vigilance (watchfulness), piety and generosity. Merriman concludes that, despite having been developed over 300 years ago, these virtues are more relevant today than ever, and as such should form a part of modern teacher education and evaluation.

It therefore follows that, to remain relevant and vital, teaching must be increasingly inspirational to foster a creative spirit and a lifelong love of learning in our students. Therefore, the purpose of this research project was to develop a model that can help teachers to understand the skills and virtues that are commonly associated with inspirational teachers and their practice, and how these can be actively nurtured, encouraged and appreciated in the schools of the 21st century.

Research methods – characterising the virtues

Secondary research – literature review

To make the findings of this study as generalisable as possible, a wide range of secondary sources were consulted, encompassing primary, secondary and tertiary education, in national as well as international institutions that included English language instruction. However, it must be noted that '*the personal and professional qualities that are most likely to inspire learners will vary according to the educational culture*' (Lamb and Wedell, 2013: 17), and therefore the findings may not apply in every educational context. Moreover, our primary data were exclusively collected from high school teachers in an international teaching context.

Primary research – open survey

Our primary research consisted of a group of 35 self-selected teachers at an international school in Singapore. They voluntarily attended a series of workshops run by the authors and completed open-response surveys before and during a lecture and discussion session.

Before the lecture, answers to the following open-ended survey questions were collected. These questions were asked before the lecture to avoid any bias in the responses and were followed by table discussions and a lecture presentation of the secondary findings. This was done to establish a shared understanding among participants of what is meant by inspirational teaching, and to help make results from the second survey more valid.

Think about a teacher who inspired you. What was it about them personally that made them inspirational?

- *What was it about their practice/behaviours that inspired you?*
- *What effect did this person have on you?*
- *Can you think of a counterexample – an 'uninspirational' teacher?*

Results

Once the open responses were collected, the task was then to group them, using secondary research to inform our categories, and tally and tabulate the results for analysis. The results from the question about uninspirational teachers were not used.

We consulted a wide range of secondary sources before deciding on the categories that we would use for the teacher virtues in this analysis. Heffernan *et al.* (2010) have *dynamism*, *rapport, applied knowledge* and *effective communication* – the latter two of these we class with pedagogy, and the first two as passion and relationships respectively. Similarly, Jensen, Adams and Strickland (2014) have four 'constituents' of inspirational teaching as '*Knowledge and passion for the subject*', '*understanding learning and knowledge*', '*constructive and challenging learning environment*' and '*students as individuals/partners/colleagues*'.

Finally, Sammons *et al.* (2014) gave six categories: *positive relationships*, *good classroom/behaviour management*, *positive and supportive climate*, *formative feedback*, *high quality learning experiences* and *enjoyment*. According to the findings of Sammons *et al.* (2016), the two most commonly cited characteristics of inspirational teachers are '*positive relationships with students*' and '*enthusiasm for teaching*'. Although other researchers have grouped them differently (Jensen, 2013), in this article, three categories were decided upon, namely *pedagogy*, *relationships* and *passion*.

Effective pedagogy

We felt it was important to distinguish between the *virtues* of inspirational teaching and the *skills* of pedagogy, as the two concepts are often conflated (Jensen, 2013). As pedagogical skills are beyond the scope of this research, findings related to good professional practice, such as subject knowledge, interactive delivery, feedback, organisation (Jensen, 2013) and good classroom management (Sammons *et al.*, 2016) were not included in the analysis.

Building and maintaining relationships

As social animals, our brains are hard-wired to connect with others (Lieberman, 2013). However, for a student to form a relationship with an adult who is not a parent or relative, the adult needs to show at least some of the characteristics that are highlighted in Table 1, as evidenced by the summary of both secondary and primary research.

Discussion

There follows a brief exploration of the nature of some of the commonly cited teacher virtues related to relationships.

Caring

It is clear from the primary and secondary research that caring is one of the most important virtues a teacher can have when building relationships with their students. Caring is defined as:

> *those emotions, actions and reflections that result from a teacher's desire to motivate, help or inspire their students … demonstrated within the broader social context of teacher–student interactions in and out of the classroom situation.* (O'Connor, 2008: 117).

Wentzel (1997: 415) suggested that middle school students more willingly pay attention in class when they think their teacher cares more and that '*when asked to describe teachers who care, students generated responses that correspond closely to dimensions of effective parenting.*'

Confidence building

Wentzel (1997: 417) describes this virtue as staff believing in students' ability to achieve, and supporting students to do the best they can, asserting that '*students are more likely to engage in classroom activities if they feel supported and valued*'.

Knowing students well

Sammons *et al.* (2014: 52) found that inspirational teachers '*made an effort to know and refer to students as individuals … some teachers merely called on students by name, others greeted each student individually at the door before the lesson began, while still others made comments that showed awareness of students' lives and interests beyond the classroom*'.

Trustworthy/reliable/honest/consistent

Students are most comfortable building relationships with adults they can trust and rely on to be consistent and honest in character. Su and Wood (2012: 150) interviewed students of inspirational teachers, and one respondent said '*with him I never felt belittled or intimidated by asking the same question twice or even going back to basics … when we start to talk about new ideas, there is always (for me) that moment when I fear I am going to make a fool out of myself … but it feels OK to make those mistakes*'. Clearly, this student trusted the teacher enough to take risks, relying on them to be honest about their mistakes, but in such a way that they were safe from negative emotional consequences. It seems almost intuitively obvious that these virtues form the cornerstone of any good interpersonal relationship.

Humorous

The use of humour in education is a delicate balancing act. Ory (2001: 9) states that '*neither the stand-up comic with no content expertise nor the cold-fish expert with only content expertise receives the highest ratings consistently from students*'. Sammons *et al.* (2016: 139) found that many inspirational teachers:

> *used humour at some point during the lesson … not so much a matter of actually telling jokes as being willing to laugh with students (for example, at the teacher's own mistakes, or as a mild way of redirecting silly behaviours), or to say unexpected things to surprise them. This helped to create a positive climate, support classroom management and promote student engagement and enthusiasm*'.

It is very important to note that sarcasm, derision and associated forms of humour are perceived as cruel and should be strongly discouraged. Humour is also highly context-specific and may be open to misinterpretation or lead to confusion in culturally diverse classrooms.

Relatable/likes children

It has been found that when students perceive similarities between themselves and others, stronger relationships result. Such similarities might include interests, personality traits, hobbies or attitudes, and may lead to greater compliance, prosocial behaviour and positive emotions towards a teacher (Gehlbach *et al.*, 2016). It follows, therefore, that teachers who discover and build upon such similarities between themselves and their students, will develop stronger relationships with them over time.

Communicating a passion for teaching and learning

If a teacher does not demonstrate a love of both their academic subject and of education itself, students may never be inspired to experience the joy of learning in science, maths, poetry or art, be motivated to learn independently, develop a lifelong passion for knowledge, or follow a career in that subject. Tables 2 and 3 show a summary of the related secondary and primary research.

Discussion

Enthusiastic/passionate

Interviews by Su and Wood (2012: 149) yielded comments such as

> *It's got to be a passion for the subject and an urge to share that with others – to get other people to be as interested in it as you are … it ought to be about exploration, illumination, and curiosity. Good lecturers 'light the match' – inspiring you to go and find out more.*

> *For a lecturer to be passionate about the subject they teach is arguably the greatest trait of all. For instance, a lecturer I had a few years ago would usually append each learning outcome with how this section we had just covered was 'the single most truly beautiful thing ever'. It was fantastic to see a lecturer genuinely enjoying what he was doing, and passing on his knowledge of that field to a new generation … His upbeat attitude was hugely encouraging. I'm certain his passion for the subject brushed off on me and others, which vastly enhanced my learning experience*

Storytelling may be a valuable skill that teachers can use to express enthusiasm for their subject (Rowcliffe, 2004).

Creative

Robson (2020) found that lecturers with a passion for teaching are more creative in their approaches to teaching, and often research or develop novel teaching methods for their learners. Inspirational teachers are also less route-specific, finding their own paths towards learning goals, compared with other teachers (Blaylock *et al.*, 2016).

Challenging/sets high expectations

Inspirational teachers are seldom constrained by prescribed learning goals; '*rather they aim to take children to their next level of understanding*' (Blaylock *et al.*, 2016: 20).

Conclusion: a hierarchical model of inspirational teaching

Over the course of this research, the concept developed of inspirational teaching as an emergent property, arising from pedagogically skilled teachers with good student relationships sharing their passion for education with their students, and links were made to Maslow's 'hierarchy of needs'. As such, a hierarchy of inspirational teaching (HIT) model, shown in Figure 1, was developed to represent a hypothetical relationship between teacher skills and virtues to facilitate discussion and inspire further thoughts surrounding teacher training and evaluation.

The HIT model suggests that pedagogical elements such as differentiation, planning, assessment for learning, classroom management, scaffolding, effective questioning, organisation, differentiation, subject knowledge and so forth, are foundational skills if a teacher can ever hope to inspire their students. It is hard to imagine an inspirational teacher whose lessons are unplanned, undifferentiated, undisciplined and unruly, with poor assessment or questioning. Any teacher who masters these skills alone can deliver effective lessons and their students will learn measurable outcomes. But just as the young Rachmaninov had to first learn his scales on the piano before transcending his paradigms and becoming an inspirational, creative pianist, teachers must first master these pedagogical skills, before they can develop into inspirational educators.

Relationships form the next stage in this hierarchy. Once a teacher has mastered pedagogical skills, relationships with students become important on the path to

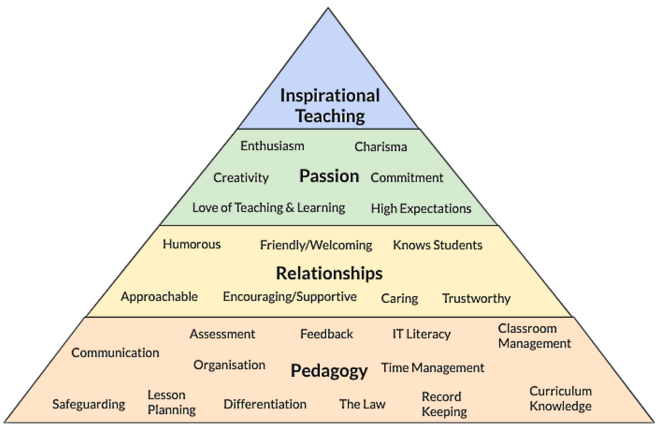

Figure 1 The hierarchy of inspirational teaching

Table 1 Virtues that build relationships

Authors	Virtues that build relationships	Tally
Sammons *et al.* (2016), O'Connor (2008), Brady (2011)	Caring	10
Jensen (2013), Bradley *et al.* (2015), Lamb and Wedell (2013), Rochford (2004), Su and Wood (2012)	Confidence building/encouraging/supportive	9
Jensen (2013), Sammons *et al.* (2016)	Knows students well	8
Heffernan *et al.* (2010), Bradley *et al.* (2015), Su and Wood (2012)	Approachable	6
Bradley *et al.* (2015)	Trustworthy/reliable/honest/consistent	5
Jensen (2013), Sammons *et al.* (2016), Heffernan *et al.* (2010)	Friendly/welcoming	5
Jensen (2013), Heffernan *et al.* (2010), Bradley *et al.* (2015), Rochford (2004), Su and Wood (2012)	Humorous	4
Brady (2011)	Prizing/accepting	3
Brady (2011)	Humble	3
Jensen (2013), Lamb and Wedell (2013)	Fun/enjoyable	3
Sammons *et al.* (2016), Lilly, Rivera-Macias and Warnes (2013)	Relaxed/flexible	3
N/A	Generous	3
Lamb and Wedell (2013), Brady (2011)	Kind/warm	2
Lilly *et al.* (2013), Rochford (2004), Lamb and Wedell (2013), Brady (2011)	Tolerant/patient	2
N/A	Community spirit	2
Gehlbach *et al.* (2016)	Relatable/likes children	1
Heffernan *et al.* (2010), Brady (2011)	Empathetic	1
Sammons *et al.* (2016)	Collaborative	1
Jensen (2013), Lilly *et al.* (2013), Rochford (2004)	Respectful	0
Sammons *et al.* (2016)	Fair	0

Table 2 Virtues that demonstrate passion

Authors	Virtues that demonstrate passion	Tally
Jensen (2013), Lilly *et al.* (2013), Bradley *et al.* (2015), Sammons *et al.* (2016), Brady (2011)	Enthusiastic/passionate	20
Lilly *et al.* (2013)	Eager to learn/love subject/interested	15
Lilly *et al.* (2013)	Engaging/charismatic/entertaining	11
Heffernan *et al.* (2010), Bradley *et al.* (2015), Sammons *et al.* (2016), Rochford (2004)	Creative	6
Jensen (2013), Bradley *et al.* (2015)	Challenging/set high expectations	6
Lilly *et al.* (2013)	Committed	2
Jensen (2013)	Interesting	2
Bradley *et al.* (2015)	Positive	0

Table 3 Factors increasing and decreasing inspirational teaching

Factors increasing inspirational teaching	Tally	Factors decreasing inspirational teaching	Tally
Flexible/supportive leadership/colleagues	18	Lack of time to build relationships with students	14
Time with students outside of lessons	14	Focus on academics/grades	14
Time to prepare/plan/create – workload	12	Excessive workload/burnout	11
Culture that students are 'more than just grades'	4	Culture that doesn't value creativity	7
Feeling valued or trusted	4	Administrative task burden	6
Access to resources	4	Lack of autonomy	4
Well-disciplined students	3	Unmotivated students	3
Student feedback	2	Lack of quality professional development	2
Autonomy	2	Unsupportive leadership	2
Smaller class sizes	1	Lack of resources	2
Not feeling stressed	1	Competitive culture	1

inspirational teaching. Students are more likely to do work for someone they like; with a caring, approachable and funny teacher who knows them as individuals, students will be more inspired to work hard and enjoy being in school, provided that teacher has first established good pedagogy in the classroom. That is not to say that a teacher cannot have good relationships with students without being pedagogically skilled, but it seems doubtful that such relationships will be based upon respect for the teacher as a professional; they may be a popular, but an ineffective and uninspirational teacher.

For a teacher to be truly inspirational, it is not enough for them to have strong pedagogical skills and good relationships with their students. They must also be passionately interested in the subject, and love teaching. It stands to reason that, if a student sees a respected professional adult with whom they have a good relationship, and that person is happy to be in the classroom and excited about what they are teaching, the student will naturally gravitate towards learning from them. As teachers, we ask our students to think like us, to listen to us, and to do the work we assign them. If we do not believe that what we are doing is important or interesting, and communicate that belief to our students, we cannot reasonably expect them to feel or behave otherwise. This hierarchy positions passion above relationships, because it seems reasonable that a passionate teacher who has excellent pedagogical skills might fail to inspire their students if they have not first formed good relationships with them. Such a teacher might come across as aloof or distant, a stranger, a 'mad scientist' or eccentric poet, for whom students might feel respect but perhaps not be inspired.

Evaluation

Limitations

In evaluating the HIT model, one might consider the three most commonly cited criticisms of Maslow's hierarchy: firstly, that it lacks empirical data; secondly, that it assumes that all individuals and situations are essentially alike; and thirdly, that there is only one right way to reach the top of the hierarchy (Kaur, 2013). In defence of the first criticism, the research presented does provide an empirical and rational basis to justify the hierarchy, and although further primary research may be demanded to prove its veracity, the inherent epistemological limitations of the human sciences may ultimately render this a fruitless endeavour. As to the second and third criticisms, some students will love mathematics, literature or science so much that they will be inspired regardless of the teacher. Some students will not need a good relationship with a teacher to be inspired by their passion and some teachers may be so passionate and charismatic that students will be inspired by them regardless of their lack of pedagogical skills. No two teachers or students are alike, and there is more than one way to the top.

Strengths

Firstly, one might consider the intrinsic value of the HIT model, as has been argued to be the case with Maslow's hierarchy, which has made a '*significant contribution in the field of organisational behaviour and management especially in the area of employee motivation and remains attractive to both researchers and managers alike*' (Kaur, 2013: 1064). Simply by providing a framework for discussion and a shared understanding and language for teachers and leaders, the HIT model might move the academic discourse around inspirational teaching forward. Roosevelt and Garrison (2018) emphatically despair of a culture that regards teachers as nothing more than '*certified mechanics*' of education, and although it is easy to dismiss their emotionally charged essay and its whimsical view of teaching as a necessarily '*soulful*', '*lovely*' and '*noble*' vocation, many of their sentiments ring true, and this model helps to formalise their ideas, as well as other nebulous concepts that exist surrounding the mysterious 'art' of inspirational teaching.

Any extrinsic value of the HIT model must lie in its application to teaching practice. Teachers who aspire to become more inspirational might reflect upon this model and ask themselves whether there are any virtues that they could develop, thus providing a stimulus for self-reflection. Such teachers may ask themselves, '*Do I show my students that I care about them?*', '*Can I be more lighthearted or humorous in the classroom or is my sarcastic humour backfiring and driving my students away?*', '*Have I taken enough time to get to know each of my students personally, so that I understand a little of their cultural background and personal interests?*', '*What opportunities exist for me to spend time getting to know my students better, either outside or inside the classroom?*'

Teachers who do not consider relationships with their students to be 'part of their job' may be encouraged to reconsider their preconceptions. How many students are turned away from a subject simply because of a poor relationship with their teacher? On the other hand, teachers who have a real passion for their subject, but are too inhibited to express this enthusiasm, may feel liberated by the knowledge that students really do value, admire and are inspired by their ability to freely express their enthusiasm. Moreover, teachers who are expressing these virtues and are inspiring their students, can come to recognise the virtues that they possess, take ownership of them, and understand with pride why they are an inspiration to their students, keep doing so, and in turn inspire other teachers to follow their example.

In discussions about the HIT model during the primary research phase, some teachers voiced concerns such as '*I'm just not a very funny person*' or '*I don't think I am a very charismatic teacher*' – negative self-beliefs that might lead them to believe that they will never be an inspirational teacher. It is therefore crucial to emphasise that nobody can be the perfect embodiment of every virtue, nor is it necessary to do so to be an inspirational teacher. Everyone has these virtues to some degree, and a growth mindset and supportive culture should enable any professional to think about how they can improve themselves. Once again, no two teachers or students are alike, and there is more than one way to the top.

In terms of practical suggestions, Jensen (2013: 12) suggests that teachers who want to be more inspirational should:

> *make it clear to your students that you care about them and believe in their abilities to achieve … consider how you can challenge students through teaching and learning activities … show consideration and respect for students … develop an approach that shares your enthusiasm and passion for the subject with your students … continually seek student feedback to develop your understanding of how students are learning … and … work with colleagues and students to review the impact of teaching and learning activities.*

Aristotle believed that virtues are like muscles that require exercise to grow, and like habits that must be reinforced by constant practice to become ingrained in our character. Becoming an inspirational teacher is about improvement and not perfection, and as teachers we can aim to get at least some of the way up the hierarchy for our students, because they will notice our efforts, and even if we only inspire one student with a love of learning and a motivation to succeed, it will have been worth the effort. Moreover, one must not forget that inspirational teaching is more enjoyable not only for the students, but also for the teachers.

Concluding remarks

While the HIT model may have some limitations, it is hoped that it might serve to facilitate discussion among teachers and educational leaders as to the nature and value of inspirational teaching practice, and hopefully suggest practical strategies teachers can use in their professional development, or inspire further research in the field. The benefits of inspirational teaching for both students and teachers, for both grades and enjoyment of school, are so evident that the actions and expenditures required to develop it can be easily justified.

Finally, following feedback that some teachers may feel mistrustful of a hierarchical model, a second model, the 'Fire of Inspirational Teaching triangle' (Figure 2) is also presented, where each of the components of inspirational teaching has equal weight and none is at a higher level than another. A spirited debate among my colleagues concluded that perhaps for young or novice teachers, the hierarchy might be more relevant, whereas for more seasoned professionals, a fire triangle model might be more appropriate. Another suggestion was to show the intersectionality in the way some virtues might be categorised by the use of a Venn diagram model (Figure 3).

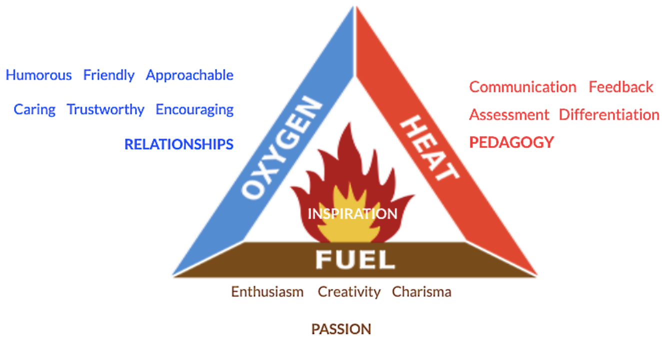

Figure 2 The 'Fire of Inspirational Teaching' triangle

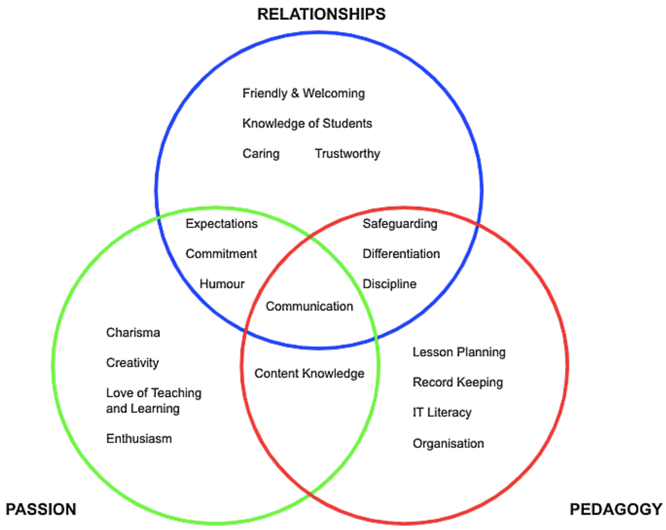

Figure 3 A Venn diagram of inspirational teacher virtues

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Teacher experience of a pandemic science intervention rooted in epistemic insight

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Abstract The COVID-19 pandemic greatly reduced students' capacities to engage in hands-on 'enquiry' science. But even before the pandemic, teachers and researchers were questioning the value and purpose of practical science. This article describes a project that imagined and then tested two answers. It imagined that the answer is to give every child their own unique experience of working scientifically. And it imagined that the answer is to help students to understand the role of science in helping humanity to ask and explore 'big questions' that bridge science, religion and the wider humanities – and so stretch across more than one subject discipline in school. The data analysed focuses on teachers' accounts of their experiences co-creating and delivering the project.

The context for the study

Education during the COVID-19 pandemic was challenging for teachers, children and parents, with the LLAKES working paper (Green, 2020) indicating that around one-fifth of school students in the UK did not engage in formal education, with often the most disadvantaged having least opportunity to learn. This amplified the recognised inequalities in students' education and science capital identified by Canovan and Fallon (2020). Focusing on the transition from primary to secondary science education, this article reports on a study that examined a practical 'hands-on' science intervention developed to counter the impact of lockdowns on students' science learning experiences, and also to enhance their understanding of the nature of science. In particular, we look at the teacher experience of using the resources developed, and their views on the student experience. Teachers recruited to the project were based in primary and secondary schools in England, working with students aged 9–12.

The interventions considered here incorporated resources to facilitate discussions around 'science and big questions' that challenge students to think out of siloed notions of subject disciplines and to draw on knowledge and experience gained in many different ways. We believe that the guiding principles behind the approach not only made it appropriate for the particular challenges of teaching during COVID-19 but also present significant opportunities for development and application in the long term.

Accessibility

Numerous factors contribute to accessibility problems in science education, particularly for hands-on practical teaching, and these were exacerbated by COVID-19 restrictions requiring home teaching and different use of classroom space and equipment. These, of course, are not unique to pandemic conditions. For example, home schooling or support for those in specialist units is a longer-term reality for many and requires tailored approaches to ensure high-quality science education is maintained.

Another contributing factor to making practical science education less accessible is lack of resources. This is frequently due to the cost of apparatus, and results in the need for group working. Small, or indeed large, group working can lead to tasks being dominated by particular individuals because of their perceived ability or force of personality. Students who lack confidence, or initial interest, are frequently excluded or self-exclude from active participation in group activities that only have a limited number of active roles. Our belief is that, in this context, observers in group work are often passive, with less learning being achieved in the activity. This issue in particular is likely to be more marked in lower-income settings owing to resource availability. We do not argue that group working lacks value, but where the only rationale is lack of resources then disadvantages do exist.

In order to address these concerns on accessibility, the interventions described below are all rooted in real-world experience, rather than abstract theoretical notions, and use low-technology equipment that is likely to be available in all schools and even most homes (Figure 1). Its low cost also means each student can have their own set of equipment. This initially allowed hands-on science in a socially distanced or home setting, but also provides the opportunity to reduce group work where this is done solely because of lack of resources.

Co-creation

An important part of the design and implementation of the study was the use of co-creation, both at the level of the higher education institutions carrying out the project and in collaboration with teachers delivering the interventions. Teachers provided important experience that helped shape the nature of the study and of interventions. Some misconceptions about the nature of science are found in stories communicated by teachers from the classroom. In one example, year 6 students (ages 10–11) failed to recall a science lesson from the previous day and even countered the teacher by stating that no science had been studied at all on that day. When the teacher reminded them of a session outside in which they had engaged in various activities followed by measurement of physiological parameters, such as pulse rate, the students responded that they saw that as PE, not science, because it was done outside in PE kit. Similarly, during the pandemic a number of students reported that science was something 'you do online', meaning that scientific information was gathered through online search engines. Both of these anecdotes suggest that the nature of science is often misunderstood and that it is frequently those on the front line who have access to the true level of misunderstanding and input into interventions.

A series of five classroom sessions was designed in a collaborative exercise involving scientists, educationists and classroom teachers. Similarly, the design of the study itself, and its implementation in various locations, was also an act of co-creation in which sampling and analysis were adapted to the reality of local conditions, which were often shifting through illness and changing guidelines. An important part of the model was that teachers were provided with all five sessions as potential parts of the intervention but with no expectation that all five would be used. In fact, only one session was used in all settings and teachers were encouraged to co-create the overall intervention for their particular setting depending upon their own skill set, knowledge of their students, their local needs and environment.

Again, this was an important aspect of accessibility and also important for our vision of a sustainable model of intervention that could be used in the longer term for all schools. In allowing teachers to use their own strengths at a time when multiple demands were being placed upon them because of pandemic requirements, it was hoped that the co-created intervention would place a lower burden on them and also engender a greater sense of confidence in delivery.

Figure 1 Each student had their own 'discovery bag', containing equipment and instructions for a simple investigation

Epistemic insight

At the heart of epistemic insight is the concept of knowing about knowing: understanding how we gain knowledge and the diverse interactions between the different ways we have of seeking to understand the world. In the context of science education, this involves a broader understanding of science and its location within the wider curriculum. Seeking to explore how science is complemented by, and complements, other subject disciplines in our efforts to answer questions and understand the way the world works helps to broaden thinking and develop new approaches to problems. In order to encourage this, we used a number of 'big questions' within the five intervention activities provided to teachers, and sought to help teachers in encouraging thought in the broader context of epistemic insight. These big questions were not simply exciting topic areas with 'wow' moments designed to catch attention. They were real-world questions that could be readily grasped by students, but which led them to deeper thought and enquiry into underlying principles of how they were coming to understand the answers they were getting.

The activities

Recent studies have shown that many students learn and think in ways that are comparable to scientists in that they observe, hypothesise, experiment and evaluate during their daily lives (Gopnik, 2012). They often question why something occurs, similarly to those who lead scientific investigations. Students are also encouraged to examine scientific concepts as they engage with their surroundings and environments (Brenneman, Stevenson-Boyd and Frede, 2009). Throughout their explorations, students become creative as they are stimulated to develop ideas and methods, reason critically and generate explanations compatible with the available information (Rossi et al., 2014). The growing body of scientific research concerning students' ability to learn

Figure 2 Students were provided with investigation cards and worksheets that contained prompts for discussion

science has helped to accentuate the potential value of science education in pre-16 compulsory education (Metz, 2009).

The interventions used in this study consisted of 'Discovery Bags', which included resources for activities to provide opportunities to explore 'big questions' bridging science, religion and the wider humanities – and so stretch across more than one subject discipline in school. Each student had their own discovery bag containing pieces of science equipment, such as diffraction glasses and coloured cards, and instructions on how to conduct a simple investigation to explore how we make sense of the universe. The teachers and students were then provided with investigation cards and worksheets that contained prompts for discussion (Figure 2).

The five intervention sessions provided to teachers all focused on questions traditionally aligned to physics and considered the following big questions by using opening science investigations:

- **Why do spinners spin?** This practical activity on gravity and air resistance, leads into the consideration of the role of observation and experimentation in science. Students are asked to explore air resistance through comparing how fast paper falls when dropped as a flat sheet and a scrunched-up ball. They then make a 'spinner' out of paper, which slows the rate of fall, and are asked to measure the time it takes to fall compared with paper in other forms (Figure 3). After considering examples of this in nature and engineering (e.g. sycamore seeds) they are then encouraged to experiment by changing the design of the spinner.
- **How do clouds stay up?** This simple activity demonstrates surface tension in water and develops the theme to consider the broader scientific concepts in the water cycle. Students start by investigating the behaviour of water droplets by placing drops onto the surface of a penny and observing what happens as they join up. This forms the basis of a further discussion about the behaviour of water inside clouds and what leads to rain. Students are then encouraged to think about their observations of clouds and other meteorological phenomena.
- **Why is the sky blue?** This question is asked in relation to the nature and diffraction of light and then as an introduction to our planet as a host for life. Students are given easily available diffraction glasses, which scatter light. When observing white light they see rainbow effects, but when asked to look at a red card they see only one colour. This

enables a discussion of the way white light is made up of different colours and how the atmosphere acts like the diffraction glasses but only lets through blue light. The discussion then leads into a consideration of the very particular circumstances of the Earth's location and conditions and its status as a 'Goldilocks' planet capable of sustaining life.

- **How do we make sense of the weather?** In this activity, measuring wind using analogues such as the movement of paper in draughts develops into how we think about the control of the weather. Students carry out an investigation in which they use a piece of tissue paper to show the movement of air from a cold room to a warm room through a small space such as a door that is slightly open. This is then discussed in a scaled-up way to think about wind and other weather phenomena of which the students have direct experience. A discussion is then encouraged on the subject of science and religion and the nature of a scientific question, initiated by the prompt question '*Does God control the weather?*'
- **In the future will people travel and live in space?** An initial consideration of the scale of the solar system expands to consider the science, politics, economics, ethics, and so on, involved in colonising space (Figure 4). Students map out the relative positions of the planets of our solar system using measurements that are given on the work card. This is used to consider the potential benefits and weaknesses of scientific models by encouraging comparison with pictures that show the planets evenly arranged in order. The students are then encouraged to think through the challenges and benefits of humans living in space in the future, firstly through the scientific and technical perspective and then through drawing on different disciplines such as economics, psychology and ethics.

A link to the resources used for all of the sessions is given at the end of this article.

Some of these questions, such as *Why is the sky blue?*, are fundamental childhood questions asked by many students as they begin to observe the world; they have ready analogues in other subject areas – such as *Why is the grass green?* for biology. Also contained within these questions are further questions about the nature of human experience and observation of the world. To continue with the example of why the sky is blue we provided information about light, the atmosphere, diffraction, and so on, but discussions on this question can easily move on to the question of our perception of colour and thus how psychology, art and other disciplines help us to understand the world and what it is to be human. We also used the opportunity of this question to consider the unique nature of the Earth's atmosphere and its location as a 'Goldilocks' planet to think about how the Earth's position enables the development of life, including human life. It is this perfect set of conditions that not only results in the sky being blue but in the existence of conscious life to ask the question of why it is blue.

Figure 3 Hands on science and agency through making paper 'spinners'

The example of the sky being blue illustrates how the entry-level questions posed in the activities were designed to engender deeper and broader exploration of subjects beyond the traditional boundaries and be a launchpad for a discussion about how we know what we know. Thus, *Why is the sky blue?* is a question appropriate not only to atmospheric science but also to psychology, art, astronomy, history, philosophy and, indeed, any number of subject disciplines, each able to provide a different aspect of the answer.

Teacher experience

In the first instance, teachers delivering the sessions received continuing professional development (CPD) training from members of the academic institutions carrying out the study. This included training on how to use the investigation cards, key learning points, the teaching notes, links to the science National Curriculum content, and how best to utilise the discussion guides. As part of this, 'style guides' were offered, which helped to provide vocabulary and grammar when talking about the nature of science, big questions and the relationship between science and real-world problems. Thus, the notion of '*observation of the natural world*' as foundational to science was reinforced as a key stage 2 (ages 7–11) objective and built on with key stage 3 (ages 11–14) objectives '*Science informs our thinking about every aspect of our lives*' and '*Some questions are more amenable to science*'.

The practical activities were designed to be used both at school and at home in the event of local lockdowns in line with contemporary COVID-19 pandemic regulations, thereby increasing the resilience of provision. Teachers were given the freedom to select which of the activities and resources they wished to use with their classes and asked to administer survey questionnaires to help assess the impacts of the interventions. In addition, teachers were asked to provide feedback on the process, content of materials and any impacts the sessions had on their own teaching and plans. Below is a summary of feedback from key stage 2 and 3 teachers, which has been grouped into three categories: confidence, big questions and learning points. All feedback was anonymous and in the form of open answers provided on questionnaires or through interviews.

Figure 4 Example of an investigation card on space

Impacts on teacher confidence

One feature of the feedback from teachers was an enhanced sense of confidence in teaching. This seemed to be, in part, associated with a sense of 'expert' support and endorsement of materials being used. As one teacher explained:

> *I found it useful to have lessons planned by someone who understands the subject at a much deeper level than me. This made it so much easier to engage the students as the teachers were so much more confident delivering the lesson.*

This, of course, points to the ongoing value of CPD, but also suggests that active interactions between classroom teachers and academic specialists have the potential to support teachers, particularly those who are less experienced or feel less 'in touch' with subject developments. This appears to be supported by teacher responses to the pre-intervention CPD, for example:

> *I learned how to explain everyday phenomena in a clear and easily understandable style.*

This was central for the purposes of this study, in which such everyday phenomena were the launching point into both understanding the scientific principles and engaging with epistemic insight aims. It is important that teachers delivering resources are confident with using them if outcomes are to be good for students, particularly in circumstances that provide additional challenges such as pandemic restrictions or isolation from mainstream classrooms. Thus, as well as providing resources and guidance notes it would seem that more active support provides enhanced outcomes. Here, this was provided through CPD sessions but was also embedded within the co-creation model in which teachers could select material they felt most confident with and could interact with investigators from the higher education institutions. While this last element will not be possible in most circumstances, the co-creation model and well-developed support materials are feasible options, provided adequate support and guidance is put in place.

Big questions

The use of 'big questions' as opposed to simply using eye-catching examples in science was an important part of the approach in this study and appears to have been a highly engaging aspect for teachers. When asked what had engaged them regarding big questions one teacher responded:

> *Finding out the answers together as a class. Encouraging students to ask the big questions, even if you do not know the answer. Fixing misconceptions to the answers to some big questions.*

This appears to show learning as a collaborative process between teacher and student, with the teacher feeling confident to explore questions without knowing the answer themselves and providing the opportunity to explore the current level of knowledge and understanding of students. When asked what had struck them most about the experience of using the resources in the classroom, another teacher replied:

> *Learning opportunities from big questions. Some may not be answered but can link to other areas, such as RE. Reinforced that sometimes we find questions difficult to answer and we may not have a definitive answer.*

Big questions, then, seemed to meet our objectives of empowering teachers to explore subject matter in a way that complemented their own strengths. Similarly, another teacher reported:

> *Great to have the big questions for a starting point and the teacher guides are helpful as give some ideas but room also to interpret to suit students.*

Here, then, the teacher highlights the aims of co-creation alongside the materials supplied. All teachers quoted here point to the value of big questions and collaborative working. Thus it would seem that it is valuable to work in a co-creative way but it is also important to formulate questions carefully to enable this to flourish; the big questions seem to have achieved this. We also deemed it important to provide clarity around what we mean by 'big questions'. This is important so that teachers can identify and work with other examples, beyond those we provided in this resource. As we learned from some of our participants and advisers, the phrase 'big questions' is widely used and with many different meanings. We therefore updated our teacher notes for future use to say, '*Big questions that bridge science, religion and the wider humanities*'.

Most important learning points

Perhaps the most important question for any intervention-based study of this nature is about transferability and sustainability. In other words, was this simply a one-off event or have any of the elements made any significant difference to teachers' understanding and plans for the future? For some teachers, there may have been little shift but for those who responded to our questions there appears to have been a range of insights and developments:

> *I will spend more time in class getting the students to think about their initial thoughts.*

> *I will frame experiments as a question to answer more often.*

> *Observation is a great way of addressing misconceptions and learning.*

> *It changed the way I taught science, to make it more hands on.*

> *The resources have encouraged me to go beyond what the age expectations are and to go more with where the students' learning is and where it can be expanded following their interests and ideas.*

> *It's great to see this link [between science and other disciplines] and it's one I intend to pursue where possible.*

> *I will use this one in class as part of our learning. I can see that some of the others would work well in after-school clubs too.*

> *It has allowed to me to use resources effectively and know even little resources can go a long way. I will allow the children more independent time to research moving forward.*

One teacher in particular indicated that this way of teaching was more akin to what she had been trained, and hoped, to do but had not been able to for various reasons:

> *On my PGCE course it was promoted, this way of learning, it really was and we were all ready to do this when I came into the job but then it was, 'you have to make sure the children have this recorded into their book' and 'you have to make sure they have done this'. I think we still want to teach this way and I think we are aware that children want to learn in this way, to direct their own learning. I think I have learnt more about the big questions – I think what we do want to do is to let children explore the ideas. I think we are aware of this and do value this and to have the opportunity to do this in the classroom.*

In several ways, then, teachers appear to have shifted their approach to teaching science or their expectations of their students. This includes:

- the use of questions rather than simply formulaic experiment-based teaching;
- the key role of observation in science;
- an enhanced role for hands-on science;
- using the model of learning to stretch expectations of students;
- using the co-creation model to align teaching outcomes with students' own interests, questions and ideas;
- applying the model beyond typical classroom situations.

Each of these provides valuable shifts and realistic expectations of change with little need for major investment or resources by individual teachers or schools.

Conclusions

While the outcomes of these interventions on student learning will be reported elsewhere, we can perhaps conclude here that for teachers there were a number of positive outcomes to using both these interventions specifically and the general model in a broader sense. Gaining confidence in subject matter for teachers is important and well recognised. In this study, we saw teachers able to use the flexibility of the materials supplied, alongside provision of guidance in vocabulary and grammar, to adapt to their own strengths and engage in bigger questions beyond immediate science content. The full co-creation model as used here may well not be practicable in all circumstances because of the scale of the study, but elements such as flexible resources, underpinning CPD and some form of mentoring may well be achievable. The ability to teach science in a research-engaged manner does not require the full resources of a university, only the correct language, frame of mind and resources. We believe that the approach of 'science and big questions' goes a long way towards the language and frame of mind. The resources produced for this study are relatively straightforward to replicate in other settings and with other questions; beginning any lesson with the question '*Why does…?*' immediately opens up possibilities for engagement and development of themes through research-based learning.

In the responses of teachers considered in this study, we find use of key terms for the nature of science, such as 'observation', but also use of interdisciplinary concepts and language to frame their experience. In this one experience, then, it is possible to see some fundamental shifts in their approach to science teaching. We do not profess that this is a complete change in approach, nor perhaps should it be, but that an intervention rooted in the co-created model and offering challenging and engaging materials, alongside formative support, can begin a process of thinking epistemologically when teaching science. Further research and longer engagement would seem necessary in order to evaluate the efficacy for students and teachers as they progress through school, but these initial results seem to show some important outcomes for teachers.

The *Investigating Big Questions* resources referred to in this article can be accessed at: https://zenodo.org/record/6556690.

Acknowledgements

We wish to thank the following collaborators who contributed to the co-creative process discussed in this article, and without whom the development and the delivery of the study would not have been possible: Berry Billingsley, Agnieszka J. Gordon, Sherralyn Simpson, Caroline Thomas, Laura Hackett, Joanna Malone (Canterbury Christ Church University); Ian Abrahams (University of Roehampton); Joy Parvin and Jane Winter (University of York); Neil Ingram and Faye Jefferies (University of Bristol); Phil Stone (Borden Grammar School); Stephen Thompson (Fulston Manor School).

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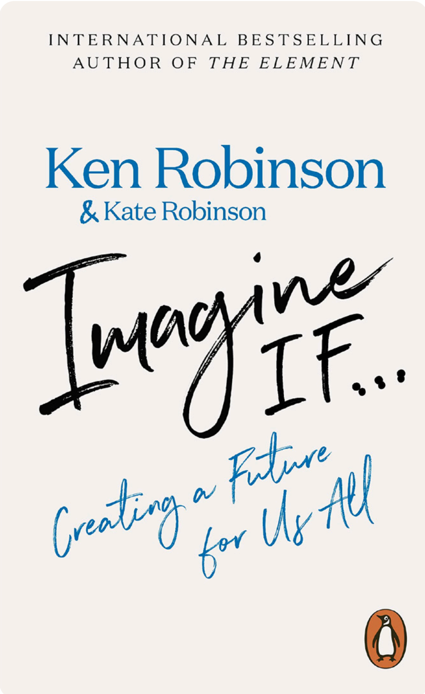
Reviews published in *School Science Review* are the opinions of individual reviewers, and are not an official Association for Science Education (ASE) view or endorsement of the resource. Reviewers are selected to write reviews on the basis of their experience and interests. They are expected to draw attention to perceived weaknesses or limitations of a resource as well as its strengths. The reviews are written from the standpoint of someone seeing the materials for the first time and considering how they themselves would use them, or think colleagues would be likely to use them.



Imagine If . . . : Creating a Future for Us All

Ken Robinson and Kate Robinson
Dublin: Penguin Books, 2022
115 pp. £9.99
ISBN 978 0 141 99097 2

Partially written in 2019 by the late Ken Robinson (before his passing in 2020) and finished off by his daughter Kate Robinson, *Imagine if . . .* is a culmination of Ken Robinson's life's work as a forward-thinking pioneer on how education can be changed for the better. This short book summarises the paradigm-shifting theoretical pedagogies that he proposed throughout his life. As much as we, as educators, aim to make the future of education as bright as Ken believed it could be, even the COVID-19 pandemic, with its repeated lockdowns giving us a chance to change how we approach education, did not achieve his dreams.

Despite the underlying theme of hopelessness throughout *Imagine if . . .* , it is an important book for educators and policymakers everywhere. It is not a book for teachers: it is a wake-up call for senior leadership teams, head teachers, governors, policymakers and most importantly, Ofsted, on how education should be judged and graded from now on.

The book discusses how education can be changed for the better across all subjects through three methods: revamping the archaic assessment system, de-siloing the subject streams and the proper development of 21st century skills.

Chapter 3, *You're more than you think*, discusses the failings of the current assessment model. High-stakes assessments based on rote learning, which barely analyse a student's critical thinking skills, mean we are not properly assessing whether students have 'learnt' their subject knowledge or are just good at reciting 'knowledge'. This is built on in Chapter 4, *The promise of education*, which discusses how education should be centred around eight core competencies, but students barely develop most of them, especially in creativity and collaboration.

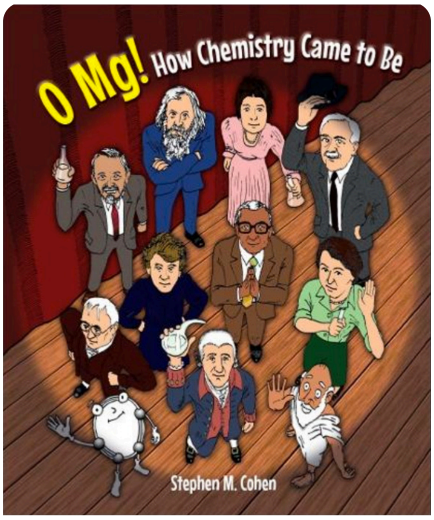
Ken Robinson argues that by encouraging collaboration between subjects, such as the STEAM subjects (science, technology, engineering, art and mathematics), students can have effective cross-curricular education that 'de-silos' each subject stream and allows each subject to use its key strengths to fully develop all eight core competencies. This is reinforced in Chapter 6, *Creating miracles*, which tells the reader that everyone, from teachers and support staff to companies and corporations, is responsible for creating a healthy learning environment for all in order to foster a culture among young people that develops a love for learning. The argument in Chapter 8, *Be the change*, about allowing teachers to foster this lifelong love for learning by removing accountability and workload pressures from teachers, is unfortunately soured by recent survey findings from the National Education Union that the majority of teachers in England are planning to leave the profession within the next three years because of increased workloads, pressure and accountability.

Ken Robinson proposes a series of plausible theoretical teaching pedagogies that could lead to an optimistic future. He believed that, if a great event caused us as a society to re-evaluate how education is taught and delivered, we would have the chance to transition education from a system designed to generate labour in the industrial revolution to a system where students would learn relevant 21st century skills. Unfortunately, we have had that great, rule-breaking event – the COVID-19 pandemic – but we, as a society, did not use that chance to make education better for future generations. Instead, we got increased accountability and more stressed students and teachers. This was a book that the world needed at the start of COVID-19 but it arrived too late. It is, however, not too late to learn from our mistakes and make the world better for future generations. I ask, no beg, that policymakers and Ofsted read this book. By working together, we can all make education relevant and worthwhile again!

Francis Jones

O Mg! How Chemistry Came To Be

Stephen M. Cohen
London: World Scientific Publishing, 2022
224 pp. £40.00
ISBN 978 981 125 040 8



After my initial scepticism at its graphic-novel format, this book has truly grown on me. It is reminiscent of the *Horrible Histories* series of books, which has cartoons interleaved with prose sometimes narrated by Rattus the Rat. *O Mg!* is pure comic strip narrated by a character called Ben Zene, an inspired choice.

O Mg! covers an extraordinary amount of material, including a nod to philosophy, in what I estimate amounts to less than 30 000 words, equivalent to maybe 70 pages of a typical popular science paperback. Perhaps this format forces the author to weigh up the inclusion of every single word. It includes explanations of chemistry as well as history, and many of the drawings are integral to this endeavour. For example, the drawings help with the 'explanation' of Stahl's phlogiston theory before it is picked apart, illustrating how the observations from successive experiments were interpreted.

The blurb on the back cover suggests that the book is aimed at secondary schoolchildren, teachers and interested adults. Parts of it may be too advanced for the youngest readers. For example, Chapter 9 covers topics such as thermodynamics, the law of mass action, the ideal gas equation, Gibb's free energy, chemical potential, catalysis and Le Chatelier's principle, and Chapter 13 touches on orbital theory. However, these sections can be skipped.

With its generous sprinkling of interesting nuggets of information (e.g. the rationale behind the naming of chemical weapons), this book will certainly be popular among geeky students, particularly those who are apt to memorise parts of the periodic table. The contents page and index mean that readers can home in on topics of interest.

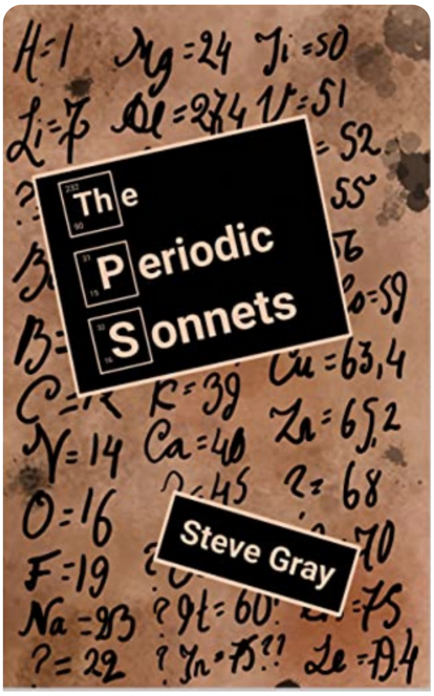
O Mg! includes chapters on industrial chemistry, polymers and nanochemistry. If nothing else, this illustrates the vast range of possible careers open to budding chemists. The chapter on environmental chemistry was my favourite, with discussions on acid rain, the greenhouse effect, photochemical smog and ozone depletion. It even mentions the role of James Lovelock, one of my scientific heroes. It sometimes strays into physics but is no worse for that.

The etymology of words used in chemistry is included. This adds interest for readers like me and makes terminology more memorable. For example, it never occurred to me that the term isotope is Greek for 'equal place' (in the periodic table), a term proposed by Margaret Todd, a Scottish GP. This is also just one of several examples where the role of various women scientists is highlighted. In an understated way, it also gives due credit to Islam and the Arab empires for incubating alchemy (the infant chemistry) through the Dark Ages until the Renaissance.

I recommend this book. Every secondary school library should have a copy and every chemistry teacher should consider purchasing one, particularly if their grasp of the historical context of their subject is a bit sketchy. Besides, it will provide a lot of anecdotes for lessons and the odd cartoon to brighten up a *PowerPoint* slide show. It should also be popular among students, particularly reluctant readers.

However, at £40 for a hardback it is a little expensive, and it is hoped that the publisher will make this book more affordable to give it the readership it deserves.

Mike Follows



The Periodic Sonnets
Steve Gray
Amazon, 2022
150 pp. £7.00
ISBN 9 798416 78979 4

Just when you think the options for presenting information about the chemical elements and the periodic table have been exhausted, another imaginative publication appears. This book of sonnets is a worthy addition to the collection and represents an astonishing labour of love for the author. Steve Gray has ably and creatively managed to write over 140 sonnets based around the individual elements in the periodic table, as well as the key scientists recognised as contributing to our understanding of the science.

Quite rightly, the author recognises that the book is likely to have something of a niche market. That said, there are plenty of people who are as fascinated by the periodic table as he clearly is, and who will enjoy dipping into this collection of carefully constructed 14-line poems at their leisure. Keeping the shape and rhyming of the sonnets necessarily means that the factual information included has had to be carefully selected, but there are sure to be some lesser-known facts for even the most knowledgeable reader to learn.

While the book's wider appeal might go beyond those with a specific chemistry background, a knowledge of A-level chemistry will certainly help the reader (as acknowledged in the introduction) and thus it may well provide some interest to post-GCSE students with a real passion for the subject. However, there is also plenty for a budding chemist in years 9 to 11 (ages 13–16) to get their teeth into.

Whatever your background or interest, you can't fail to be impressed when reading these sonnets. There are inevitably far more comprehensive resources available on the periodic table if budgets are tight, but these sonnets are fun, informative and very carefully thought out.

Janet Mitchell

Reviewers

Mike Follows teaches physics (and is Head of Junior Science) at King Edward's School, Birmingham.

Francis Jones is a chemistry teacher at an inner-London state school and is studying part-time for his Masters in STEM Education at King's College London.

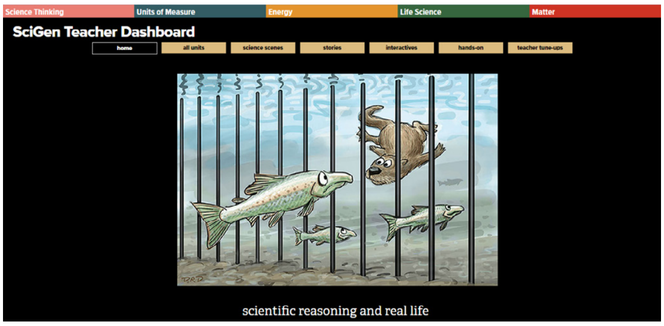
Janet Mitchell is a recently retired chemistry teacher living in Surrey.

Science websearch

- Websites are checked as close to printing as possible – however, website addresses do change.
- Inclusion of a website does not imply that ASE endorses the content of the site.
- Sites are suggested on the basis of 'take a look, you might find something interesting and useful' – we have not read every page on every website listed.
- Some sites may involve subscriptions and/or payment for download of material.

Please send details of any websites you have found or produced to the *Science websearch* editor, Sarah Sephton at sarahsephton7@gmail.com. We would also be interested in hearing about how you have used websites that have appeared in *Science websearch* in your educational setting.

In this issue, after the regular entries collated by Sarah Sephton, we have a special set of entries on the themes of electricity generation and data visualisation from Jon Tarrant.



SciGen Teacher Dashboard

https://serpmedia.org/scigen/index.html

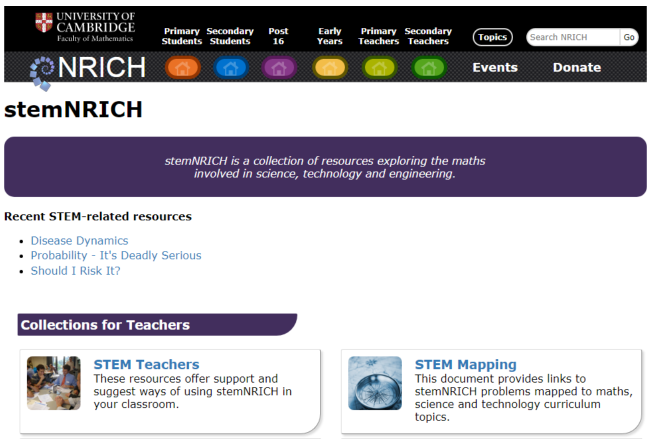
The resources available on the *SciGen Teacher Dashboard*, which have been generated by the Strategic Education Research Partnership (SERP) in America, are impressive. They are arranged in topics: *Science thinking*, *Units of measure*, *Energy*, *Life science* and *Matter*. Upon selecting the topic *Matter*, as an example, there are three units available. Each unit contains a *Reader's Theatre* script, a lesson, interactive quizzes and reading activities with accompanying detailed teaching notes. All the resources are of a high quality and are downloadable, but a free and straightforward site registration is required to access the resources.

Thinking Science

www.stem.org.uk/system/files/elibrary-resources/2018/11/THINKING%20SCIENCE.pdf

This STEM Learning Centre document called *Thinking Science* has questions aimed at 11- to 14-year-old students to '*provoke thinking and discussion*' and would be perfect summer classroom activities to get students talking about science as well as to consolidate their year's learning. Alongside physics, biology and chemistry questions, the document has 'working scientifically' questions such as '*Is there any knowledge that it would be better not to have?*', '*What would society be like without science?*' and '*How much evidence do*

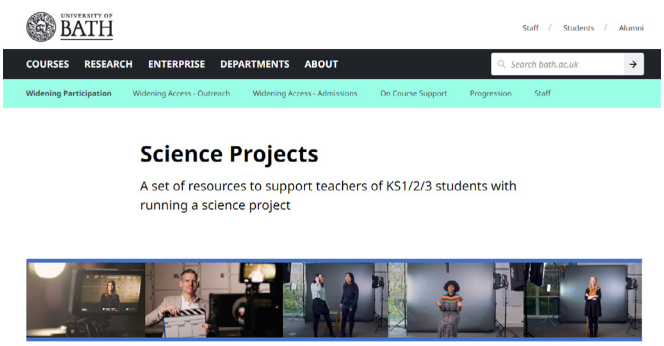
we need to conclude that a hypothesis is true? Should it be different for different situations?' All the questions include helpful detailed teacher guidance.



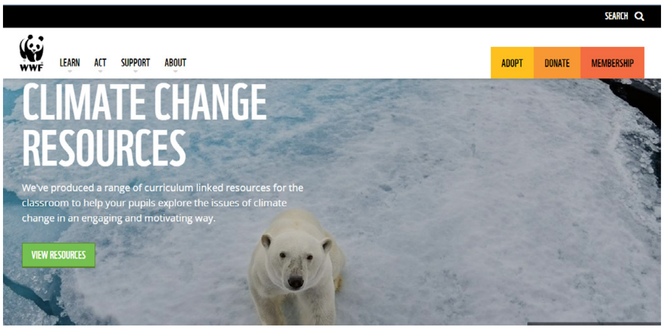
https://nrich.maths.org/stemnrich

The University of Cambridge *stemNRICH* site has a great collection of resources that explore the role of maths in science and engineering subjects. The *Maths meets Biology* section, for example, has activities organised by age and challenge level including *Investigating epidemics*, *Counting dolphins* and *Solving* *the genome puzzle*. The site also has an engaging feature in the form of *Live problems*, for which students can submit their solutions, which may get published on the site. *stemNRICH* is a well organised and interesting site, which in my opinion is well worth a visit.

www.ase.org.uk/ks3-active-learning-resources
This is an excellent collection of resources from ASE to encourage active learning in the classrooms of 11- to 14-year-olds. As well as activities organised by science subject, there is a *General* section, where I particularly liked the accompanying description, '*activities such as lesson starters or refreshers designed to get pupils feeling awake and ready to learn*', as I immediately thought of some of my classes in the last lesson of the day. Examples of activities in this section include: *Audience cube*, which requires students to throw a dice in order to determine the audience for their written or verbal answers, for example, an old grandparent or a tabloid newspaper, and *Write a short poem*, which explains how to write a very short poem on a key word, for example, 'friction'.



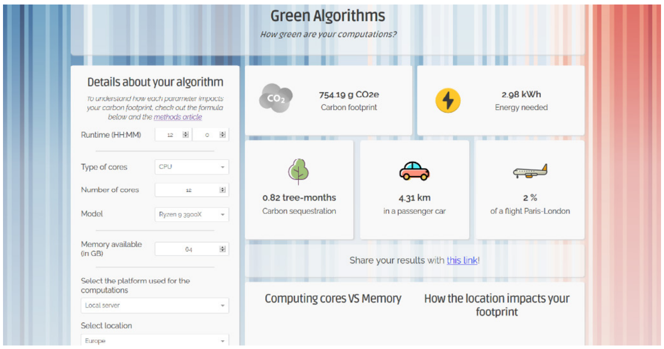
www.bath.ac.uk/case-studies/science-projects
This University of Bath website has well-prepared resources for science projects organised into the different age groups. For example, in the section for 11- to 14-year-old students, there is an attractive downloadable student workbook, *PowerPoint* presentation and lesson plans. If you are looking for something to do with your students that is fun but still ticks the 'following a scientific method' box then I would recommend this collection.



www.wwf.org.uk/get-involved/schools/resources/climate-change-resources
The World Wildlife Fund (WWF) has produced a set of resources that explore how climate change is affecting our world. The activities have age-appropriate guidance and include interactive presentations, worksheets and teacher notes on topics such as: *The climate challenge*, *Chance to change the future* and *The future we want*. A further interesting activity is an environmental footprint calculator; after answering a few multiple-choice questions, your carbon footprint is calculated and compared with the UK average and the world average – quite an eye-opening activity!

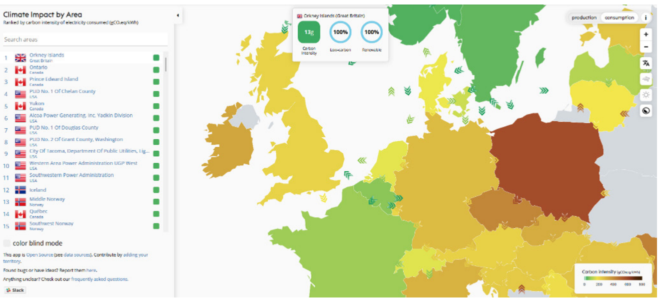
Electricity generation and data visualisation

Collated by Jon Tarrant



Green Algorithms
www.green-algorithms.org
Green Algorithms is intended to raise awareness of the environmental impact of professional scientific simulations and data analysis but it can also open a door to classroom discussions by exploring the CPUs that keen gamers have in their computers at home. For six hours of runtime, the lightweight AMD A9-9425 SoC, which is favoured in modest laptops, is revealed to have a carbon footprint of 45 g of CO_2, whereas a typical Ryzen 7 3700X has a footprint of just under 200 g and a more potent Ryzen 9 3900X is close to 400 g. Those figures, which are also given as road miles and flight equivalents, as well as carbon sequestration (in tree-months) are all based on UK electricity supplies. The website reports that the

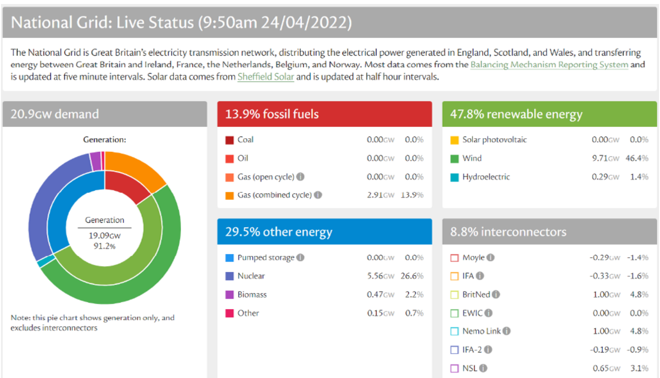
footprints would be lower in Switzerland and Sweden but much higher in China, India and Australia.



Electricity Map

https://app.electricitymap.org/map

More details about the environmental impact of regional electricity generation can be gleaned from *Electricity Map*, which displays live data for production and consumption worldwide. Island regions are normally top: often Prince Edward Island (Canada), but on the day of review, Orkney Islands was the global leader with carbon dioxide equivalent emissions of just 13 g kWh^{-1} from 100% renewable sources. On the same day, 22 April, the UK as a whole was emitting 243 g kWh^{-1} with 40% of requirements coming from renewable sources. Windy days (more than sunny days) reduce the UK's carbon footprint, to around 100 g kWh^{-1} or slightly less, with up to two-thirds of electricity from renewable sources. As well as being identified separately, renewables are included in the 'low-carbon' category, which is important since a low number here can penalise regions even if they have significant levels of renewables. Poland, for example, has 31% renewables but only 33% low-carbon in total as 60% of its electricity comes from coal, so it is brown on the map.



National Grid

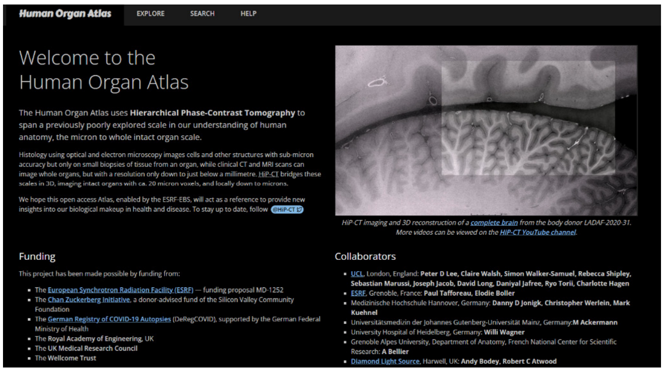
https://grid.iamkate.com

Kate Morley's website provides much greater detail about the energy sources used specifically for UK electricity generation and, crucially, the level of current demand. This is a fantastic resource that I have used in the classroom on many occasions, not least because its real-time information allows students to see how things change on a half-hourly basis. The figures don't exactly match those shown simultaneously on *Electricity Map* (described above), probably due to how the data are aggregated, but they are in the same ballpark. Regular monitoring reveals that the UK obtains higher percentages of its electricity from renewable resources when demand is low, especially on warm but breezy days. The displayed yearly averages show a massive decline in the UK's reliance on coal (down from 15.6 GW in 2012 to 0.78 GW and now falling to zero), together with the gradual erosion of nuclear (down from 7.5 GW to 5.4 GW), as well as a substantial growth in wind power (up from 1.4 GW to 8.1 GW). Nevertheless, when conditions are less favourable or demand is higher, students will see that combined-cycle gas clearly remains the UK's go-to resource to fill the gaps.

Healthmap

https://healthmap.org/en

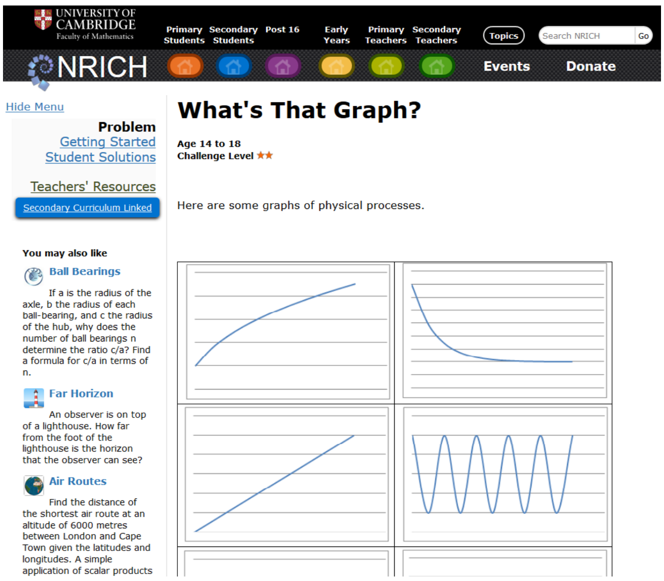
Its name might suggest that *Healthmap* is a visual guide to the prevalence of diseases around the world, but the website actually displays information about medical alerts, rather than illnesses themselves. By default, alerts are for the last seven days but this can be extended to one month in map view and a year for the tracking tool. The range of infectious diseases listed is vast but not all have alerts attached to them in the specified period; none were returned when searching for feline leukaemia virus, for example. In map view, individual markers can be clicked to view the alerts, which can then be clicked for full details – although some links do not open. Many of the alerts come via *Google* but they originate from sources as diverse as *The Fiji Times* and *Voice of America*. Note that marker windows can only be opened one at a time and they have to be closed by clicking on the 'x', as double-clicking the marker has no effect. Although this slows things down when browsing, this tool has definite classroom potential and may also be useful for form time as thoughts turn to the summer holidays and far-off travel.



Human Organ Atlas

https://human-organ-atlas.esrf.eu

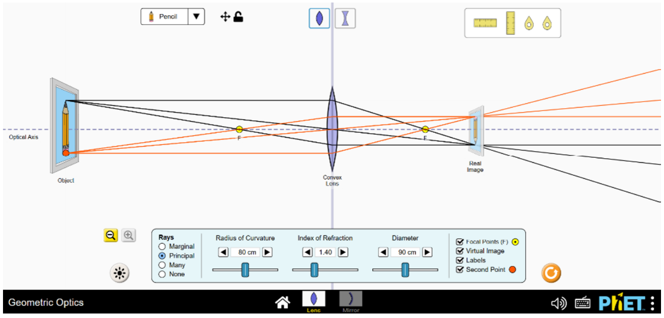
Data visualisation is also at the heart of *Human Organ Atlas*, a new project providing highly engaging, zoomable images that allow viewers to delve deep inside the human body. Only a few organs have been completed so far, but the aim is to compile an explorable image of the entire body, down to micron level, starting with a complete torso that the team hopes to have ready by 2025. The images, created using hierarchical phase-contrast tomography (HiP-CT), are intended for medical analysis but also provide a useful resource to inspire and intrigue science students. For easier access, pre-compiled 'zoom-in' sequences are available under the *Videos* tab on the team's *YouTube* channel, a link to which is provided below the embedded example on the *Human Organ Atlas* website.



NRICH (Mathematical Modelling)

https://nrich.maths.org/9070

All of this data visualisation serves to remind us how essential mathematical skills are for the sciences. Step forward NRICH, a long-running initiative from the Faculty of Mathematics at the University of Cambridge that has been helping to develop the next generation of problem-solvers for 25 years. Of particular interest to science teachers is the *Mathematical Modelling* section, which includes activities related to *Graphs*, *Big and small numbers in physics*, *Speed–time problems at the Olympics*, and an entire set of resources exploring *Disease Dynamics*. The activities are graded by difficulty and age, from early years through to A-level. During the summer holiday, from 18 July until 31 August, NRICH will again be posting a series of daily challenges for both primary and secondary students, at https://nrich.maths.org/primary-summer2022 and https://nrich.maths.org/secondary-summer2022 respectively.



PhET (Lenses and Mirrors)

https://phet.colorado.edu/sims/html/geometric-optics/latest/geometric-optics_en.html

Finally, away from electricity and data analysis, it is good to herald the arrival of an HTML5 version of geometric optics from PhET, which this year celebrates 20 years of online simulations. Mirrors and lenses are covered in separate sections, both with enough controls to make initial explanations simple while also providing opportunities to develop learning in more detail later. Mirrors can be planar or curved and the object can be moved to illustrate, for example, the change from an inverted real image to an upright virtual image in the case of concave surfaces. Lenses can be analysed using principal rays from either one or two points on the object, and I particularly like the *Many Rays* option, which reminds students that there are countless rays available, despite the common use of just three rays to image each object point.

Contributors

Sarah Sephton, editor of *Science websearch*, is a chemistry teacher at St Clement Danes School in Chorleywood, Hertfordshire.

Jon Tarrant is a former Head of Sciences. He is the creator of physbang.com and the author of seven books on photography.

SSR special issues

Year	Month	Volume/ number	Theme	Special Issue Editor(s)
2009	June	**90**(333)	**Active in space**	David Bowdley
2009	December	**91**(335)	**Chemistry essentials and enhancements**	Colin Osborne
2010	March	**91**(336)	**Biodiversity**	Sue Howarth and Neil Ingram
2010	September	**92**(338)	**Education for sustainable development**	Marcus Grace
2011	March	**92**(340)	**Small-scale science**	Bob Worley and Geoff Auty
2011	June	**92**(341)	**The inspiration of Marie Curie**	Averil Macdonald
2011	December	**93**(343)	**Contemporary topics in school science**	Tim Harrison
2012	March	**93**(344)	**Space for education; education for space**	Allan Clements
2012	June	**93**(345)	**Science behind the Olympic Games**	Geoff Auty
2012	December	**94**(347)	**Earth science**	Chris King and Cally Oldershaw
2013	March	**94**(348)	**Half a century of ASE**	Edgar Jenkins and Valerie Wood-Robinson
2013	September	**95**(350)	**Public understanding of science**	Michael Hal Sosabowski
2013	December	**95**(351)	**ASE's Summer Celebration Conference**	Annette Smith
2014	March	**95**(352)	**Perspectives on the science curriculum**	Andrew Hunt
2014	September	**96**(354)	**Energy and climate change**	Keith Ross
2014	December	**96**(355)	**STEM – linking technology, engineering and mathematics with science**	Gill Collinson
2015	June	**96**(357)	**Practical work I**	Michael J. Reiss
2015	September	**97**(358)	**Practical work II**	Michael J. Reiss
2015	December	**97**(359)	**Science, literacy and learning**	Ruth Jarman and Billy McClune
2016	March	**97**(360)	**Mathematics in science**	Richard Needham
2016	September	**98**(362)	**Science during primary–secondary transition**	Sue Collins and Michael J. Reiss
2016	December	**98**(363)	**The attraction of space**	Geoff Auty
2017	June	**98**(365)	**Epistemic insight** **New GCSEs**	Berry Billingsley and Mark Hardman
2017	September	**99**(366)	**Public understanding of science** **ASE schools exhibition**	Michael Hal Sosabowski
2017	December	**99**(367)	**Epistemic insight II**	Berry Billingsley and Mark Hardman
2018	March	**99**(368)	**Epistemic insight III**	Berry Billingsley and Mark Hardman
2018	June	**99**(369)	**ASE Annual Conference 2018**	
2018	September	**100**(370)	**Framing the secondary science curriculum**	Anthony Tomei
2018	December	**100**(371)	**Science and society** **ASE schools exhibition**	Ralph Levinson with Ruth Amos, Marie-Christine Knippels and Eleni Kyza
2019	March	**100**(372)	**Everyday science**	Keith Ross
2019	June	**100**(373)	**ASE Annual Conference 2019**	
2019	September	**101**(374)	**The periodic table** **ASE Annual Conference 2019 II**	Michael Hal Sosabowski
2019	December	**101**(375)	**The periodic table II** **ASE Annual Conference 2019 III**	Michael Hal Sosabowski
2020	March	**101**(376)	**Science, engineering and big questions**	Berry Billingsley
2020	September	**102**(378)	**The role and relevance of science in addressing global concerns**	Berry Billingsley
2021	March	**102**(380)	**Science and health care**	Geoff Auty
2021	June	**102**(381)	**Science education and nature**	Marcus Grace and Janice Griffiths
2021	December	**103**(383)	**Science education in the context of the climate crisis**	Lynda Dunlop and Elizabeth Rushton

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