November 2023 Volume 105 Issue 389

SSR in Depth

School Science Review

ASE's peer-reviewed journal for 11–19 science education

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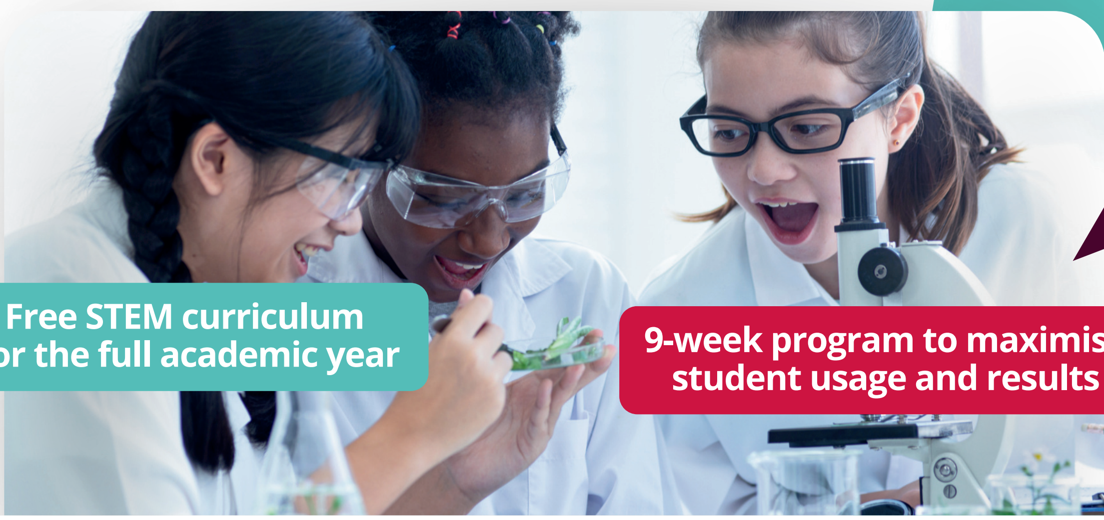

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The ASE's peer-reviewed journal for 11–19 science education

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SSR in Depth

The ASE's peer-reviewed journal for science education 11–19

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 Editors, ssreditor@ase.org.uk. 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;
- all recognised hazards have been identified;
- 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*.

Unless the context dictates otherwise it is assumed that:

- practical work is conducted in a properly equipped laboratory;
- any mains-operated and other equipment is properly maintained;
- any fume cupboard operates at least to the standard of CLEAPSS Guide G9;
- care is taken with normal laboratory operations such as heating substances or handling heavy objects;
- 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

Fiona Williams, *SSR* Content Editor

Welcome to the November issue of *SSR*. As you will see, there has been a lot of activity behind the scenes to apply the new brand to the journal. There is a great mix of articles in this issue – I hope that there is something for everyone.

SSR's inaugural photo competition ran over the summer break. Thank you, everyone, who took part in the competition. We had some stunning entries, and you can see the winning and runner up photographs on page 35 of *SSR in Practice*. I would like to showcase the striking pictures taken by twins Charlotte and Patrick, aged 9½. Our youngest entrants have done a splendid job in capturing 'light in the natural world'. Well done!

Photo by Charlotte Hoath

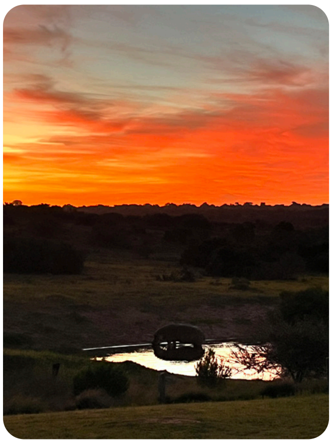

Photo by Patrick Hoath

In *SSR in Practice*, we have included a selection of book reviews written by students on books with a chemistry theme that they have chosen themselves. These reviews have been written by students who are studying science at post-16 and would like to study a scientific discipline at university. It can be difficult to keep abreast of the various popular science books that might be of interest to our students. We hope that you can share this centrefold with your students.

In the area of real-world science, Andy Markwick's articles provide insight into some recent developments in the extraction and recycling of E-metals using deep eutectic solutions. E-metals are those that are used in electronic-based technologies such as batteries, electric motors and smart phones. As we look to move away from fossil fuels, this is an important area, given our increased use of transportation, technology and communication. The article in *SSR in Practice* contains an overview of the extraction and recycling of E-metals and provides great context for teaching, while, in *SSR in Depth*, the use of deep eutectic solution chemistry is explained as an environmentally friendly way of extracting and recycling important E-metals.

In *SSR in Depth*, David Read and Stephen Barnes report the findings of their study into topics that chemistry teachers find difficult, one of these being electrochemistry, while, in *SSR in Practice*, Jennifer Marchant brings to life the topic of electrochemistry with some real-world examples.

Inclusion is very topical at present. Fiona Roberts shares some practical adaptations for students with SEND – a vital read for all as we strive to make our classrooms and teaching inclusive for students with a range of individual needs. In a second article on inclusion, Carole Kenrick writes about her experiences of putting into practice the IOP guidance on inclusive science teaching; it is a very relevant article for teachers of all the sciences.

Finally, on page 36 of *SSR in Practice*, Helen Harden (Commissioning Editor) writes about ways that you can contribute to *SSR*.

This is your journal. As such, we want to read about and share in your knowledge and practice. If you have never written for *SSR* before and are unsure whether your article idea is suitable then please get in touch with Helen at helenhardenase@gmail.com

Fiona Williams

Read more in *SSR in Practice*

SSR in Practice **is available at:** www.ase.org.uk/ssr-in-practice/issue-389

ASE Presidential Address: Science education at a time of existential risk

Michael J. Reiss

Abstract Quantitative measures of human wellbeing, such as child mortality, the percentage of people in absolute poverty and the percentage of children who have no education beyond primary level, suggest that, globally, things are getting better for people. But what of existential risks from asteroid impacts, climate change, artificial Intelligence, genetically modified organisms, pandemics, nuclear war and ecosystems collapse? How much of a risk are these to humanity and should school education address such risks?

Background

This article is based on the Presidential Address that I gave at the 2023 ASE Annual Conference in Sheffield. I hope this allows me to start by being personal. I grew up in London in the 1960s and early 1970s. A bookish schoolboy, I did my A-levels early in applied mathematics, pure mathematics, chemistry and physics and went up to university to read physics. Within ten days I realised I wasn't a physicist; it was simply that I had been taught almost all the physics I ever learnt by a superb teacher, Colin Harris, who had inspired me to think that I too could read physics at university. I quickly changed to biology and soon fell in love with it. I stayed on at university and did a PhD on evolutionary biology and population genetics, focusing on red deer, and then did a post-doc.

While doing my PhD and post-doc I had taken advantage of the fact that Cambridge encouraged postgraduate students to supervise undergraduates in small groups of two or three. I soon discovered that I found this very satisfying. As my post-doc drew to a close, I decided, rather at the last minute, to apply to do a PGCE and was fortunate to be accepted. My PGCE year was in 1982–83; I joined the ASE in 1982 and have been a member ever since.

Is the world getting better or worse?

Looking back on it, for the first four decades of my life, I rather unthinkingly presumed that things were getting better for humanity. My parents and their generation had lived through the Second World War and there was clearly a widespread, albeit generally unspoken, presumption that never could anything like that be allowed to happen again. However, since the dawn of the millennium, I have become less optimistic about the future. Even before we get to the existential threats to which I turn below, there are reasons for concern. For example, democracy, which had made huge advances internationally during my childhood and early adulthood (think the fall of the Berlin Wall and the ending of many dictatorships in Europe, South America and elsewhere), feels as though it is increasingly in retreat. And while medicine continues to make great advances, there are gathering storms from such things as antibiotic resistance, mental health issues and problems resulting from the diets that many of us consume.

A number of authors, however, argue that things are getting better for humanity, indeed are better now than they ever have been (e.g. Pinker, 2018; Rosling, 2018). These arguments tend to follow the same form. Numerical data are presented on graphs, where the horizontal axis indicates the date – e.g. from 1800 to 2015 – and the vertical axis indicates some quantitative measure of human wellbeing, such as child mortality, the number (or percentage) of people in absolute poverty, the number (or percentage) of children who have no education beyond primary level, and so on. A good selection of such graphs (e.g. Figure 1) can be viewed on

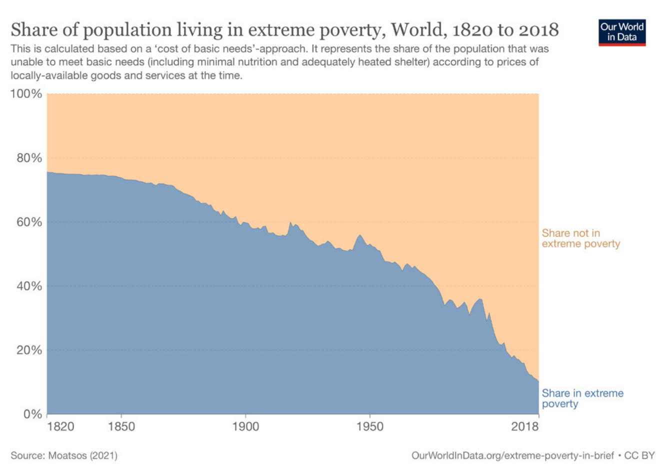

Figure 1 An example of a graph intended to show how things are getting better for humanity (source: *Our World in Data* https://ourworldindata.org)

the *Our World in Data* website (see *Useful links* below), which currently has some 3580 charts. The general message seems to be that we should stop complaining and do something to help those less fortunate than ourselves.

One response to these claims that things are getting better is to point out that there can be something of a disconnect between these apparently objective measures and the frequent subjective experiences of individuals. No one, for example, is against falls in poverty but it is possible for poverty to fall while income or wealth inequalities are rising and the consequences of such inequalities can be surprisingly widespread and negative. In their book, *The Spirit Level: Why More Equal Societies Almost Always Do Better*, Wilkinson and Pickett (2009) argue (graphs, again) that greater inequalities are associated with falls in such measures as physical health, mental health, happiness, trust and social mobility, and with rises in such measures as obesity, drug misuse, under-age pregnancy, violence and crime. Furthermore, these rises and falls are overall, that is, not just among those who are losing out in terms of relative income or wealth. The argument is that societies would do well to reduce inequalities.

Comparable points can be made about most of the other measures that are paraded to show us that things are getting better. Take life expectancy, for example. Over the last century or so, life expectancy has increased greatly across the globe, in part a result of improved sanitation and agriculture, in part a result of improved medicine, and also in part a result of other technological advances (in communications, transport and so on). However, (a) these increases in life expectancy are currently stalling or even reversing in many countries, only partly, but not entirely, as a result of the COVID-19 pandemic, and (b) it is not the case that greater longevity necessarily equates with greater happiness or life satisfaction. Many people do indeed live longer than they would have done in the past but they live longer in poorer health. In many countries we do not deal well with the final phase – which may last many years – of our lives (e.g. Gawande, 2014).

A second response is that these claims that things are improving are fine so far as they go but that we are living at a time when there are far greater threats, often referred to as existential, not only to humanity but often to other species too. It is these threats that are my principal focus.

Existential threats

An existential threat is one that is believed to be capable of preventing continued existence. Perhaps because this tends to suggest apocalyptic fictional literature and films (think the long history from such books as Mary Shelley's *The Last Man* and *Frankenstein* through H. G. Wells' *The Time Machine* and *The War of the Worlds* to more recent offerings such as the films *Bladerunner*, *The Terminator* and *The Matrix* and their sequels, and *Interstellar* and *Snowpiercer*), it can be difficult to take such threats seriously. In any event, it is well known that humans are not very good at understanding and dealing with risk (e.g. Adams, 1995).

Nevertheless, there are a growing number of organisations and academic thinktanks devoted to existential threats, including the University of Cambridge's Centre for the Study of Existential Risk, the University of Oxford's Future of Humanity Institute, Stanford University's Existential Risks Initiative and the Future of Life Institute, a non-profit organization with the mission statement '*Steering transformative technology towards benefitting life and away from extreme large-scale risks*' (see *Useful links* below). In addition, there are the beginnings of serious philosophical examinations of these threats (e.g. MacAskill, 2022) to back up existing work, which is largely scientific and technological.

In no particular order, I now go on to examine seven possible existential threats: asteroid impacts, climate change, artificial intelligence, genetically modified organisms, pandemics, nuclear war, and ecosystems collapse.

Asteroid impacts

Of all the possible existential threats, an asteroid impact might sound the most like science fiction and there is a fictional film genre that starts with *When Worlds Collide* (1951) and *The Day the Sky Exploded* (1958) and goes through to *Don't Look Up* (2021). Except that, as is widely known, it is likely that it was the impact of an asteroid 10–15 km in diameter some 66 million years ago that led to the mass extinction event that ended the Mesozoic Era. It is thought that around 75% of all animal species went extinct as a result, including all non-bird dinosaurs, indeed all animals with a mass greater than about 25 kg (Osterloff, 2020).

There is a growing academic literature on the threats to Earth from asteroid impacts – see Sokolov *et al.* (2020) and also Pultarova (2020), which has the apt title 'Predict, deflect, survive – How to avoid an asteroid apocalypse: asteroid impacts are the only natural disasters that can be predicted but also avoided …'. It is still somewhat unclear both how much a threat such impacts are and to what extent we will be able to prevent them. What is clear is that such impacts happen. In 1908 an asteroid or comet thought to be about 30 m in diameter exploded above ground in Tunguska,

Figure 2 A 1929 photograph showing damage caused by the Tunguska asteroid impact in 1908 (source: https://commons.wikimedia.org/wiki/File:Tunguska_Ereignis.jpg)

Russia (Figure 2). The explosion has been calculated to be about 1000 times more powerful than the explosion of the atomic bomb over Hiroshima. Fortunately, it happened in a remote part of Siberia and no one is thought to have been killed, although 80 million trees were knocked over (The Planetary Society, 2023).

Climate change

Few readers of *School Science Review* will be unaware of the threats posed by climate change, including global warming. I am old enough to remember, when at school, a *New Scientist* article that talked about the possibility of global cooling. There were two reasons why global cooling was thought a possibility in the 1970s, even though it was already known that atmospheric levels of CO_2 and other greenhouse gases were increasing. One reason was simply that we are currently in an interglacial – indeed, on the law of averages, we ought to be entering another Ice Age now. The second was that it was thought possible that the cooling effect of aerosol pollution might outweigh the warming effects of additional greenhouse gases. A survey of the scientific literature found that between 1965 and 1979, 44 scientific articles predicted warming, 20 were neutral and seven predicted cooling (Le Page, 2007). Now we appreciate the extent to which global warming is already happening (Figure 3) and some of the other ways in which climate change is manifesting itself: rising sea levels, increases in ocean acidity, more extreme weather events, and so on.

It is difficult to know how great a risk to humanity global climate change poses. My lifetime has shown negligible evidence that the world's leaders are taking global climate change with any seriousness and I, for one, found COP27 at Sharm el-Sheikh in Egypt in November 2022 to be a somewhat depressing affair. Of course, the Earth has had some pretty extreme climates in the past. Some 600–800 million years ago, in the Neoproterozoic

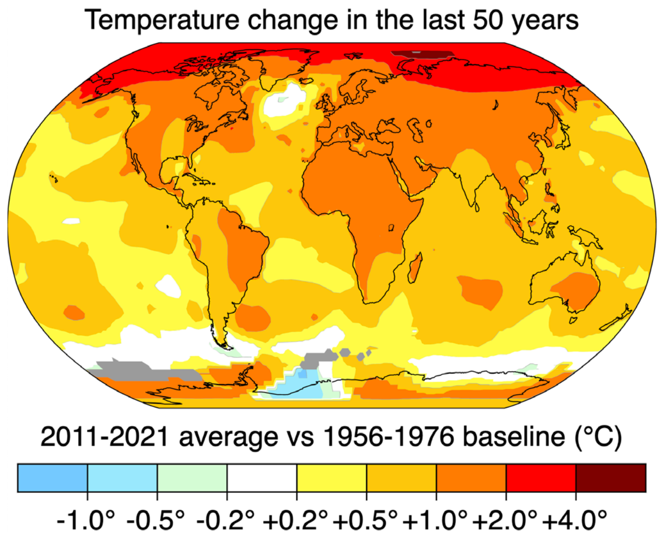

Figure 3 Global warming over the last 50 years (source: https://commons.wikimedia.org/wiki/File:Change_in_Average_Temperature.svg)

era, ice sheets may have extended from the poles all the way to the Equator (Scott and Lindsey, 2020). At the other extreme, some 92 million years ago, champsosaurs (crocodile-like reptiles) lived in the Canadian Arctic, and warm-temperature forests flourished near the South Pole. The biologist in me is therefore confident that life on Earth will survive anthropogenic climate change, albeit with very considerable ecosystem damage and substantially raised extinction rates.

Artificial intelligence

There is a wide diversity of views about the potential for AI, ranging from overenthusiastic pronouncements about how it is going imminently to transform our lives to alarmist predictions about how it is going to cause everything from mass unemployment to the destruction of life as we know it (e.g. Bostrom, 2014). AI is already here; it is already making a huge impact in almost every aspect of manufacturing and there are sensible predictions that it will be used increasingly in a large number of professions, including medicine, law and social care, not to mention education (Reiss, 2021).

Although it may sound like science fiction (*2001*, *Ex Machina*, *The Matrix*), serious concerns have been raised about the possibility of AI posing an existential threat. Indeed, Nick Bostrom (2014), the founding director of the above-mentioned Future of Humanity Institute at Oxford University, believes that of all the existential threats, AI is the one most likely to lead to the extinction of humanity. Bostrom's key concern is what happens when we get to 'the singularity', the time at which we have an AI (a digital computer, networked computers, cultured cortical tissue or whatever) that greatly outperforms the best human minds in practically every field. At that point, AI really may take over and there is a risk that it might decide that its ends can better be met without humans. Even if things aren't quite as apocalyptic, Bostrom likens the relationship between such superintelligence and humanity to that that currently exists between humans and gorillas, where the continued existence of gorillas depends on whether humans want them to exist or not.

Genetically modified organisms

Concerns about genetically modified organisms (GMOs) may seem rather 20th century now (Reiss and Straughan, 1996). While concerns were raised about the safety of foods made from GMOs, these have not come to pass. Indeed, there is an ongoing argument about whether the greater use of GM crops might improve human health. For instance, so-called 'golden rice' is a variety of rice modified to produce, through genetic engineering, more beta-carotene, a precursor of vitamin A. Rice is a staple crop for about half the world's population, and vitamin A deficiency is thought to cause about 250 000–500 000 children to go blind each year, about half of whom die within 12 months of losing their sight.

Fears that GM crops might run riot have also receded. Such fears should not be dismissed out of hand but crops are not very hardy and it seems likely that the accidental or intended introduction of non-GM plants, such as Japanese knotweed (*Reynoutria japonica*) and water hyacinth (*Pontederia crassipes*), into unfamiliar habitats will continue to cause far greater problems.

Pandemics

Few people know that the infectious disease that has killed the most humans over the last two centuries (records before that time are poor in quality) is tuberculosis (TB), caused by the bacterium *Mycobacterium tuberculosis*. Even today, some one- to one-and-a-half million people die from it each year. The advent of COVID-19 has made most of us more sensitive to the dangers posed by infectious diseases. Long explored in films (e.g. *Contagion*) and novels (e.g. Stephen King's *The Stand*), the risks of pandemics are not to be dismissed. COVID-19 has probably killed about 15–20 million people to date, some 0.25% of the world's population. The 1918–1919 influenza pandemic (Figure 4) probably killed about 50 million people, some 2.5% of the world's population at the time.

Figure 4 Camp Funston, at Fort Riley, Kansas, during the 1918 influenza pandemic (source: https://en.wikipedia.org/wiki/Camp_Funston)

International agencies often place pandemics at the top of their list of threats to humanity, with a new infectious disease arising about every eight months (Mishra *et al*., 2023). Despite this, the same international agencies invariably conclude that the risks from future pandemics remain largely ignored and underfunded. To a biologist it seems difficult to imagine that we won't in the next generation or two experience a pandemic with worse consequences than COVID-19. At the same time, humans have evolved to have an impressive system of defences against infectious organisms – against which our ancestors battled for many millions of years. Contrary to the views of science fiction writers, it seems unlikely, given both our natural immunity and vaccinations, that the large majority of people will die at the hands of an infectious organism. (I am prepared to issue an apology to ASE members in the event of this forecast proving mistaken.)

Nuclear war

Declaration of interest: I have been a member of CND for over 40 years. In 1947 the scientists who had worked to develop the first atomic weapons in the Manhattan Project created the Doomsday Clock. They used the imagery of apocalypse (equated with midnight on the clock) to convey threats to humanity and the Earth, and set the clock at seven minutes to midnight. The decision as to whether to change the time on the clock is made every year by the Bulletin of the Atomic Scientists' Science and Security Board. In January 2023, the Board moved it to 90 seconds to midnight, the closest to midnight that it has ever been.

How much of an existential threat would nuclear war be? In 1982, atmospheric scientists Paul Crutzen and John Birks suggested a nuclear war would produce a smoke cloud so massive that it would cause what became known as a nuclear winter. Climate modelling suggests that the reduced sunlight would lead to a fall in global temperatures by up to 10 °C for a decade. The consequences for global food production would be catastrophic. Everything depends, of course, on the scale of the conflict but a recent academic article predicted that '*more than 2 billion people could die from nuclear war between India and Pakistan, and more than 5 billion could die from a war between the United States and Russia*' (Xia *et al.*, 2022: 586).

A nuclear disaster might be unintended. There is a *Wikipedia* page titled *List of nuclear close calls* (see *Useful links*). It is not recommended for those of a nervous disposition. To give just one example, on 26 September 1983, Lieutenant Colonel Stanislav Petrov was the duty officer at the command centre for the Russian nuclear early-warning system when the system reported that a nuclear missile had been launched from the United States, followed by up to five more. Petrov judged the reports to be a false alarm and disobeyed orders to launch a retaliatory nuclear strike. Had he not done so, it has been estimated that about half the population of the countries of the Soviet Union and NATO might have died. A subsequent investigation confirmed that the Soviet satellite warning system had malfunctioned (these things happen …).

Ecosystems collapse

Finally, we turn to ecosystems collapse. There is a danger that this might happen to farming ecosystems as a result of soil damage or climate change and to natural ecosystems as a result of habitat destruction or climate change. The word 'collapse' is apposite as the point is that the effects of often very long periods of harm are only perceived suddenly. This has happened with commercial fisheries. A classic instance occurred in 1992 when North Atlantic Cod populations fell to 1% of historical levels, primarily as a result of decades of overfishing. In Newfoundland alone, approximately 37 000 fishermen (it was a very gendered profession) and plant workers from over 400 coastal communities lost their livelihoods. Recovery of the fish stock has taken substantially longer than anticipated and it has been estimated that this may not happen until about the year 2100.

To give one more example, permafrost is soil or underwater sediment that continuously remains below 0 °C, and so is frozen. Permafrost is abundant – in the Northern Hemisphere, it is almost the combined size of the United States of America, Canada and China. However, it is melting fast (Figure 5). Once it melts, it can take a very long time to recover, even if the climate becomes cooler; it can get washed away and its very large carbon reserves may become oxidised. One of the worries is that positive feedback is involved: rising temperatures (and human-induced temperature

Figure 5 Thawing permafrost in Herschel Island, Canada, 2013 (source: https://commons.wikimedia.org/wiki/File:Permafrost_in_Herschel_Island_018.jpg)

rises are greater where permafrost is found than anywhere else) lead to loss of permafrost, which leads to carbon oxidation, which leads to enhanced CO_2 production, which accelerates global warming.

Existential threats and school science education

There is a danger in simply adding more and more to the school science curriculum but I think there are two arguments as to why existential threats might profitably feature more than they do. One is simply that I suspect that for many students they provide 'engaging' contexts for routine science teaching. Consider asteroid impacts, for instance. Learning about projectiles in physics is not always the most motivating of activities; for some students, examining the consequences of asteroids of different sizes striking the Earth might be interesting. Students will also rapidly appreciate that an understanding of Newtonian mechanics is needed but not sufficient. All of the existential threats considered in this article are examples of what are sometimes called 'wicked problems' – problems that cannot be unambiguously solved and that require contributions from a range of disciplines if they are to be meaningfully addressed.

The second reason for school science courses dealing with existential threats more than they currently do is that for humanity (including politicians) to begin to address these threats we need more people to have a good understanding of them. School science can play an important role in helping people to begin to appreciate both the nature and the extent of these threats for humans and for other species.

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Useful links

Our World in Data: https://ourworldindata.org
University of Cambridge's Centre for the Study of Existential Risk: www.cser.ac.uk
University of Oxford's Future of Humanity Institute: www.fhi.ox.ac.uk
Stanford University's Existential Risks Initiative: https://seri.stanford.edu
Future of Life Institute: https://futureoflife.org
Wikipedia, *List of nuclear close calls*: https://en.wikipedia.org/wiki/List_of_nuclear_close_calls

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‘*Really disliked it at A-level. Never truly understood it.*’ Identifying topics in which chemistry teachers lack confidence

David Read and Stephen M. Barnes

Abstract Chemistry is a challenging subject for its students and those who teach them. A teacher’s subject matter knowledge (SMK) is the foundation on which their pedagogical content knowledge (PCK) is founded, and is the basis of successful teaching. Flawed SMK can result in teachers holding misconceptions that are then transferred to students. In this article, we report the results of a survey of chemistry teachers that probed their views of their own SMK, its development and its importance. Key findings are the identification of electrochemistry as the topic that teachers are least confident in teaching, along with other topics in which teachers lack confidence, thus providing guidance to those responsible for teachers’ initial training and subject-specific CPD providers.

It is widely recognised that chemistry is a challenging subject for those who study it. The abstract nature of chemistry concepts can lead to misunderstandings among students, which hamper their progress (Zoller, 1990). As these concepts are crucial in developing a meaningful understanding of chemistry (Taber, 2002), it is imperative that they are well understood by students. If they are not, this can lead to the development of misconceptions.

Similarly, it is crucial that science teachers understand the subject matter that they teach (Abell 2007; Van Driel, Berry and Meirink, 2014) to ensure that their students can comprehend it (McConnell *et al.*, 2013). Coe *et al.* (2014) cite six components necessary for great teaching, that is, ‘*that which leads to improved student achievement using outcomes that matter to their future success*’. The first component is *‘[pedagogical] content knowledge’* (PCK), as there is robust evidence to suggest that this has an impact on student outcomes (Hill, Rowan and Ball, 2005; Sadler *et al.*, 2013). The RSC also argue that good subject matter knowledge (SMK) is essential in good teaching:

> *The best teachers are those who have specialist subject knowledge and a real passion and enthusiasm for the subject they teach ... the Royal Society of Chemistry believes that young people deserve to be taught the sciences by subject specialists.* (RSC, 2004, quoted in Kind, 2009: 169)

This article discusses the key findings from a teacher survey, with a particular focus on confidence levels in different topic areas. It is intended that this article will provide guidance to those responsible for teachers’ initial training and subject-specific CPD providers.

Methodology

The survey questions were grouped into five main sections:

- Demographic information
- Impact of teacher training
- Subject matter knowledge for chemistry
- The A-level curriculum and beyond
- What makes a good teacher?

For the data obtained to be meaningful and easier to interpret, three types of question were used in the survey. Simple yes/no questions and Likert scales were used for participants to share opinions and make the data quantifiable. In addition, open-response questions were included, many being coupled with yes/no or Likert scale questions to give participants the opportunity to provide explanations. The survey was initially trialled with four A-level teachers, with amendments made to ensure that the desired data and level of response would be received. Ethical approval was obtained via the university’s ERGO system, with BERA guidelines being followed.

The survey was publicised via email to an outreach mailing list (207 teachers), via email to subscribers to *Education in Chemistry*, and publicly via *Twitter*, resulting in 51 responses. Completion times were typically between 45 minutes and one hour. All participants who responded to the online survey were self-selecting, and therefore the dataset obtained represents a convenience sample. Responses to closed-response questions were quantified and tabulated or graphed. Responses to the open-response questions of the survey were analysed by content analysis using NVivo (Versions 11 and 12) software.

Analysis of teachers' responses to questions and prompts in the 'SMK for chemistry' section of the survey are discussed below.

Results and discussion

The undergraduate degree and confidence in chemistry teaching

To explore the perceived influence of the undergraduate degree on SMK, participants were required to respond to statements 1a and 1b using a five-point Likert-type scale:

> *My undergraduate degree provided me with enough chemistry subject matter knowledge to feel confident teaching GCSE chemistry.* (1a)
>
> *My undergraduate degree provided me with enough chemistry subject matter knowledge to feel confident teaching A-level chemistry.* (1b)

After providing responses, participants were prompted to briefly explain their choices (Figure 1).

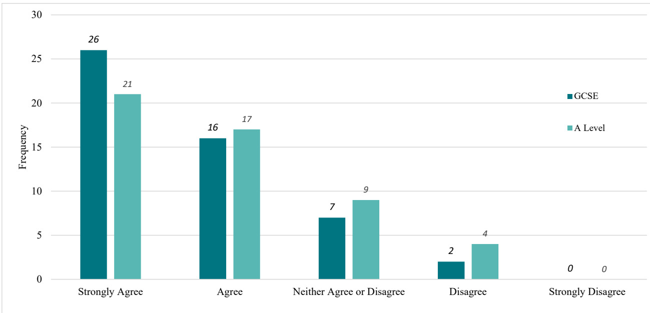

Figure 1 Teacher responses to statements 1a and 1b

Responses were positive overall, with 82.4% (n = 42) strongly agreeing or agreeing that their degree provided them with enough chemistry SMK to feel confident teaching at GCSE level, and 74.5% of respondents (n = 38) strongly agreeing or agreeing regarding teaching at A-level. The high level of agreement reveals a belief that the completion of a degree has provided enough SMK to give confidence in teaching. Some teachers reported views that assert the value of a chemistry degree to a chemistry teacher, which are pertinent given the increased preponderance of non-specialist teachers:

> *I am able to stretch those from GCSE to A-level and then beyond, [based on] my own education.*

Some teachers noted gaps in their knowledge and understanding despite holding chemistry degrees, emphasising the importance of SMK development during ITT and beyond (Kind, 2014):

> *My major problem was that I never fully understood the subject. So when I went to university again these gaps in my knowledge were never filled in (from both GCSE and A-level). [It] took until I started teaching to realise this.*
>
> *I've had some issues with subject knowledge when teaching A-level. Some students have questioned me and I have had quite a weak understanding and only surface learned some topics.*

One teacher acknowledged the limitations of a chemistry degree in developing teacher knowledge:

> *I think it's very important to understand where student misconceptions appear from and how to challenge them with care. Degree programmes don't do this; teacher training should do this but from my experience they definitely didn't.*

An important element of a teacher's awareness is what their students know and don't know, to provide a meaningful educational experience (Ausubel, 1968). This awareness should include an understanding of misconceptions, so that a teacher can easily identify and challenge these misconceptions at source. This comment supports the need for specific training on misconceptions and implies the contribution of experience to a teacher's PCK (Grossman, 1990).

The extent of a teacher's SMK

Participants responded to statement 1c below using a five-point Likert-type scale, with their responses being illustrated in Figure 2:

> *In relation to subject matter knowledge, a teacher of A-level chemistry should be an expert in their field.* (1c)

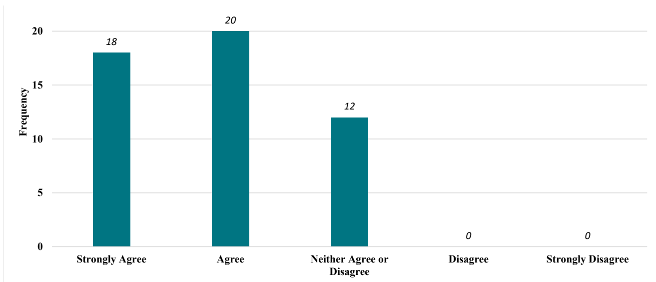

Figure 2 Teacher responses to statement 1c

The overall response to this item was positive, with 76.0% of respondents (n = 38) strongly agreeing or agreeing that an A-level chemistry teacher should be an expert in their field. It is not surprising to see that no participant disagreed or strongly disagreed with this statement, as many teachers may perceive themselves as experts. Among those who strongly agreed or agreed with statement 1c, the most prominent theme was the requirement for knowledge beyond the specification (n = 14). Representative quotes include:

In order to gain pupil confidence you need to know your stuff ... how much of an expert you need to be may be up for discussion but you need knowledge beyond the A-level spec.

You need to have a grasp of what lies beyond A-level, even if it is a hazy fuzz from years ago. It helps frame the teaching you do post 16 and pre 18.

Confidence was also observed to be a prominent theme in the responses of those who agreed with statement 1c. These participants justified their agreement with the statement through arguing that to communicate content effectively, a teacher must be confident in their SMK:

This goes without saying. If you are not an expert it will be obvious to students and you will lose their confidence quickly. You need to be an expert to clearly deliver the content.

It is a challenging A-level. A teacher who is not secure in their knowledge cannot develop confident learners.

It was acknowledged that teachers may not begin their careers as experts, highlighting the importance of strong SMK in making links between different concepts, something that is integral to strong PCK (Hashweh, 1987). This also aligns with Childs and McNicholl's (2007) assertion that a teacher cannot plan effective lessons until they have mastered the content themselves:

Only now I have taught the organic topics a few times do I feel confident – this is perhaps becoming an expert in those topics and this allows me to be a much better teacher, make curricula links as well as explaining clearly why things happen.

Similarly, a number of responses (n = 9) related to teachers having an awareness of their students' learning and interest in chemistry:

All teachers should be experts in their field, otherwise it devalues teaching and education. Pupils have the right to be taught and inspired be someone who has a deep interest and love for their subject.

Students will find it hard to be inspired by someone who they do not consider an expert.

Some participants agreed with statement 1c with the caveat that it depends on the definition of 'expert'. Eight of 12 participants who selected the 'neither agree or disagree' option cited this in their reasoning, with some suggesting that a high level of expertise can be detrimental to teaching ('*the curse of knowledge*' – Camerer, Loewenstein and Weber, 1989):

Depends what is meant by expert. I have been taught by people who are 'experts' i.e. at the cutting edge of research who have not been able to explain things very well.

These comments imply that there is a link between having a high level of SMK and a low level of PCK (in this case how to convey fundamental ideas in topics of great expertise), similar to the findings of Harris and Sass (2007).

Two teachers referred to the fact that you don't need to be an expert from the beginning of your teaching career, and that experience is essential in developing expertise:

I don't think it's realistic to expect a teacher to be an expert in the specification content of a subject from the word go, but it's something that they should be working towards over the course of the first few years of their teaching career.

Other participants emphasised that higher levels of knowledge allow for discussion beyond the specification:

You should always be ready to go beyond what is needed. A student might ask a question that needs a higher level of understanding. For example, a Y7 once asked how the hi-vis stripes on his cycle helmet worked; some 6th form students guessed that there was a link between Gibbs free energy and equilibrium. It was good to be able to explain these ... and grab their interest.

Teacher workload was cited as a problem by one respondent, emphasizing the importance of developing SMK during training and in the early stages of a career in teaching:

Not having a suitable subject qualification to teach chemistry makes workload much higher ... teachers rarely have the time in their day to day work to top up their subject knowledge.

Participants were asked if they were confident in their SMK before they started teaching, and were then asked if their confidence changed once they started teaching (Table 1).

Table 1 Teacher ratings of confidence in their SMK before and after starting teaching

Before teaching	After teaching	No. of respondents
Not confident	No change	1 (2.0%)
Not confident	Confidence increased	9 (17.6%)
Not confident	Confidence decreased	1 (2.0%)
Confident	No change	18 (35.3%)
Confident	Confidence increased	17 (33.3%)
Confident	Confidence decreased	5 (9.8%)

Responses from participants who reported increased confidence after teaching include:

Confidence improved the more I taught and reflected.

Once teaching my confidence improved as I gained curriculum knowledge.

Responses from participants who reported decreased confidence after teaching include:

I realised how much I had forgotten (or possibly never knew).

The gaps in my knowledge ... were now exposed.

Two salient quotes highlighted the need for the teacher to understand the conceptions that students bring with them to the lesson – and, of course, those of the teachers themselves:

Realised that to teach I had to get below the level of the students to make sense of what they were trying to do with their knowledge.

Your understanding can be excellent, but without a thorough understanding of how students can misunderstand your subject then you will find it difficult to teach them.

Methods of SMK development

Participants were asked whether chemistry SMK development was a compulsory part of their ITT, with a small majority (53%) indicating that it wasn't. Quotes from respondents who did experience SMK development during ITT indicated that coverage was patchy. 73% of respondents indicated agreement or strong agreement with the statement that '*Training providers should offer more SMK development support during teacher training*'.

One participant explicitly stated that the SMK development in their ITT course was '*very poor*', due to a focus primarily on GCSE level chemistry content but no A-level content. As has been previously noted, it can be said that a specialist degree is not necessarily an indicator of strong SMK (Kind, 2014), and it can be argued that ITT providers should therefore work more with pre-service teachers on enhancing their SMK.

When participants were asked if they undertook self-directed SMK development during training, only 61% reported that they did. In a majority of cases, this involved the use of textbooks, while use of past papers was another commonly cited approach. A number of respondents emphasized the importance of working with non-specialist teachers to develop their SMK:

I find new colleagues coming into teaching with less specific degree courses (chemistry teaching with a forensics degree or biochemistry degree) who find the more technical and mathematical topics a challenge to teach.

People on my course without a strong chemical background really needed more subject help.

Other respondents cited the challenge of squeezing SMK development into already packed ITT programmes:

A very tricky one for providers – there is a huge range of other parts of ITT that need to be covered in a very short time.

It is up to an individual as to what they want/need to do to prepare. There are enough resources out there for someone to use if they need to develop their SMK. Teacher training should be focused around skills needed as a teacher.

To investigate how continual SMK support can be provided for teachers following Qualified Teacher Status (QTS), and to provide insight into the methods and resources that could be used, survey participants were invited to respond to question 1d:

In your opinion, what can teacher training and CPD providers do in order to support A-level chemistry teachers with their subject matter knowledge development after they have qualified? (1d)

Some illustrative responses to this question are given below:

Provide SKE for established teachers in well-known trickier topics, e.g. electrochemistry and kinetics.

When new specifications come out, have CPD courses ***before*** *they have to teach the new spec, bridging the gap between old and new specs.*

This is essential for topics which are new to the syllabus in particular (e.g. TOF mass [spectrometry]).

Nine participants commented on the importance of communication with other teachers, and how it is important for CPD and other sessions to be available in school settings:

Providing resources that can be adapted to in-school/school group settings so more expert teachers can deliver/support other teachers.

It is difficult because teachers can be as bad as students in asking for assistance if they don't know something. More informal meetings between newly trained teachers and experienced teachers of the same specifications may help.

Some of these participants noted that local chemistry teacher networks are valuable in developing teaching skills, reporting that having opportunities to share good practice with others has been beneficial in developing SMK and PCK. Five participants reported that having access to online events would be an effective way of providing SMK enhancement.

Identification of high and low confidence topics

Participants rated their confidence in their ability to teach ten A-level chemistry topic areas, ranking them from 1 (highest confidence) to 10 (lowest confidence). The ten topic areas were chosen based on a review of the content of the UK's A-level chemistry specifications (Read and Barnes, 2015). The responses to this question are detailed in Figure 3.

Atomic structure and molar calculations is the topic that participants are most confident in teaching:

> *Underlying concepts which get studied often, so I have lots of practice with it.*

> *A fundamental topic that you must know well in order to explain and teach and absolutely necessary to the understanding of the rest of chemistry.*

Nine of the survey participants commented that organic chemistry was a topic of high confidence because they enjoy its problem-solving nature, which is notable as this is known to cause difficulties for learners:

> *I like structures and mechanisms. There is an element of filling the gaps if you don't know the exact reaction.*

> *It's possible to see the big picture and get [the students] to understand the key principles that they can then apply.*

Twelve participants ranked analytical techniques among their three least confident topics. A lack of experience teaching the topic was the most-cited explanation. Two participants reported that the level of study was a cause of low confidence, but for opposing reasons. One participant remarked that the level that it is studied at during the undergraduate degree is '*not helpful*' for A-level teaching, in that it is too in-depth, while the other noted that there is a '*lack of familiarity from GCSE*'. One participant mentioned that there is a '*lack of good practical [sessions]*' to support learning of the topic, making it harder to provide relevance and context. Those with high confidence discussed its relevance to their previous jobs.

Very few survey participants ranked the topics of chemical equilibrium and kinetics in their top four. For equilibrium, participants remarked that they did not have much experience of this topic and found it difficult to simplify. For the kinetics topic, nine participants remarked that the mathematics behind understanding the topic were too difficult:

> *Some of the mathematical applications solving Arrhenius equations means that it can be difficult to help pupils pinpoint errors.*

> *Purely Arrhenius equations and rearranging as I only have GCSE level maths.*

The explicit reference to the Arrhenius equation in these comments indicates a need for SMK support when A-level specifications are changed.

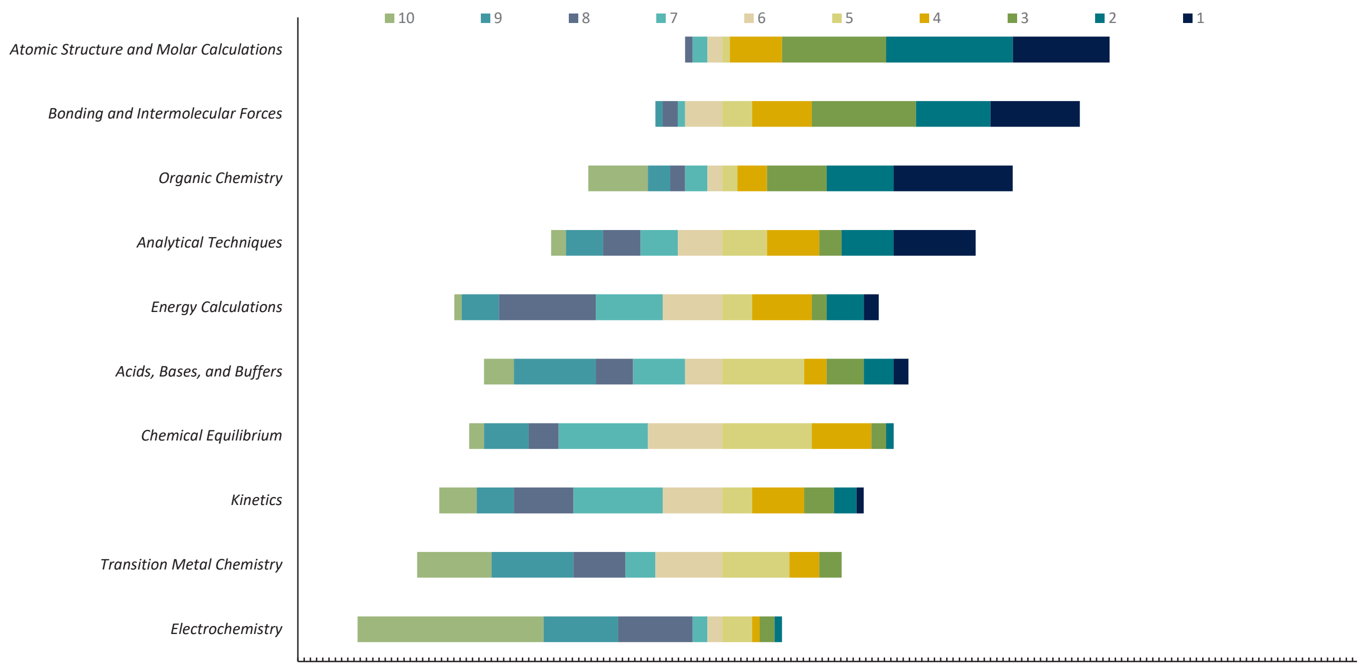

Figure 3 Teacher ratings (n = 57) of their confidence in teaching different topics, where 1 = most confident and 10 = least confident

The finding that both transition metal chemistry and electrochemistry appear in the bottom two positions is significant in highlighting a general lack of confidence in these topics across A-level chemistry teachers of different experience levels and backgrounds:

[Transition metal chemistry] was not part of my degree /PGCE course.

I did not do this at A-level.

Not studied in detail at degree.

Six participants cited their lack of experience teaching the topic as a reason for their low confidence, as observed elsewhere. Their remarks are in agreement with the assertion that a teacher's PCK develops with greater classroom experience (Grossman, 1990; Magnusson, Krajcik and Borko, 1999; Van Driel, Beijaard and Verloop, 2001). The main reason given for lacking confidence in transition metal chemistry was the amount of rote memorisation required:

Principally because the level of understanding doesn't really have a lot of explanation behind it. So it feels more along the lines of this is what happens and this is how you apply it. Not much why.

For electrochemistry, the most common reason given for lacking confidence was that teachers found it difficult when they studied it themselves (n = 17):

I did not understand electrochemistry during my degree.

Really disliked it at A-level. Never truly understood it.

Negative feelings relating to ability at university to answer questions.

Three participants attributed their unease with electrochemistry to the way it is covered on A-level specifications, with one participant stating that A-level *'doesn't give satisfactory explanations, so students often ask questions I find difficult to answer'*.

Further to these comments, seven participants reported that electrochemistry can be a confusing topic for students, with a further six remarking that terminology can lead to further confusion and misconception development:

I find that pupils tend to get themselves in a muddle over different rules.

Brings together equilibrium with a number scale that runs from negative to positive, always seems to cause confusion.

One survey participant commented on the link between electrochemistry and physics and how this can cause confusion:

There can be conflict with the physics department on precise definitions and my weaker background in electrochemistry means I am less confident with my explanations.

This comment infers that the teaching of fundamental concepts in physics (e.g. the direction of current flow), at both GCSE and A-level, may not fit with how electrochemistry is taught. For those who are required to teach both physics and chemistry, this could be problematic. As detailed by Garnett, Garnett and Treagust (1990), the compartmentalisation of science subjects is a potential cause of misconceptions in electrochemistry, in addition to inadequate prerequisite knowledge. Four further participants reported a lack of interest in electrochemistry as the reason they felt less confident in their ability to teach it.

Conclusions and future work

The conclusions are presented with the caveat that the sample size is small, meaning that the findings may not necessarily be extrapolated onto the wider population of chemistry teachers. The data nonetheless provide valuable insights for ITT and CPD providers.

The identification of transition metal chemistry and electrochemistry as near-universal topics of low confidence is an important outcome of this project. In future, it is recommended that resources and CPD courses should be developed in order to enhance A-level chemistry teachers' SMK in these areas. Further to this, investigations on the relationship between the level of a teacher's SMK and their confidence in it could also be undertaken, in order to ascertain further whether improving teacher confidence can have a positive impact on student learning. Participating teachers, including both novice and experienced teachers, felt that ITT providers should offer more SMK development support during ITT. Although the nature of ITT involves the coverage of a large amount of information and pedagogical theory, there is a clear desire for trainees to have resources available to them. Participants identified that more focus should be given to topics that are difficult to teach. Given that these topics have been identified in this study, work can be undertaken in future to develop resources to facilitate this focus. Participants also requested to approach topics from different perspectives, and focus on common misconceptions, feedback and action plans, and putting concepts in the context of practical work. These factors should be considered in the development and evaluation of any resources created in future.

Finally, numerous issues discussed by participants in this study related to issues with specialist language and terminology, an issue that has been identified in numerous studies (Garnett *et al*., 1990; Taber, 2000; Taber, 2002). Further investigation into the aspects of language and terminology that cause difficulty for students and teachers should be considered, in addition to inquiry into the methods that can be used to ameliorate teachers' concerns regarding terminology. If such methods can be identified, it would be beneficial for resources for teachers of all experience levels to be developed that can attempt to tackle these problems.

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A glimpse into the future: using deep eutectic solvents for environmentally compatible extraction and recycling of important E-metals

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Abstract Transitioning from hydrocarbon-driven economies to those that are carbon-neutral, eco-friendly and are driven by increasing concerns about global catastrophes and underpinned by the need for social justice is an imperative. This article explores the chemistry of deep eutectic solvents and their potential to be used for the extraction and recovery of E-metals, which are in ever-increasing demand. We consider whether these new technologies, which are considered environmentally benign, will offer a solution to the increased requirement of E-metals.

The transition away from energy-intensive pyrometallurgic processes, which also have a large CO_2 footprint and introduce harmful pollutants into the environment (Cl_2, NO_x, SO_2, H_2S, cyanide, concentrated acids and alkalis and arsenic), towards cleaner technologies that can drive us towards a sustainable future, requires a significant increase in the application of E-metals (Padwall *et al.*, 2022). Jenkin *et al*. (2016) state that the increased demand for these metals will not be met by extraction from new mineral sources alone, and Hsu *et al*. (2019) argue that recycling of E-metals that would normally be destined for landfill sites is critical. Certainly, there is a need to consider ways to optimise the extraction rates of E-metals from their ores and to find ways to recycle and recover E-metals from waste, whether this is current or historic, that is, recovering E-metals from already-discarded sources in landfill sites.

For several decades the application of biotechnologies to extract metals has been trialled, particularly from 'hard to get to places' and with some success. However, there have been health and safety concerns about using microbes in such large quantities with the recognition that more research is required (Jerez, 2017). More recently, intense research has focused on the properties of a unique group of chemicals called ionic liquids (IL). IL are salts that are anhydrous liquids that contain ions and, like aqueous counterparts, they are electrolytes and excellent solvents. Investigations have shown that ILs are very effective at extracting metals from scrap metal and metal oxides (Abbott *et al.*, 2017). Unfortunately, although the use of IL for the extraction of metals is less energy intensive, many are relatively expensive and are often toxic to the environment.

An alternative group of related solvents was first investigated by Professor Andy Abbott's team, based at the University of Leicester, which they termed deep eutectic solvents (DES). These are mixtures of chemicals such as choline chloride (vitamin B4 and quaternary ammonium salt) and urea or citric acid (Abbott *et al.*, 2004). When mixed in the correct proportions (eutectic composition – see later) and at temperatures below 100 °C, they form anhydrous solutions that are excellent solvents for metals and metal ores. The solvents are environmentally benign, biodegradable, and low cost in terms of both precursor chemicals and energy consumption. In comparison to other solvents, they leave a very low carbon footprint (Smith, Abbott and Ryder, 2014).

Jenkin *et al*. (2016), also from the University of Leicester, showed that DES can be used for the extraction and recovery of metals in E-waste and from metal ores. Jenkin's team were able to demonstrate the effective extraction of metals such as Au and Ag using the DES ethaline (1 mol choline chloride: 2 mol ethylene glycol) with 0.1 mol dm^{-3} iodine as an oxidising agent (Abbott *et al.*, 2015; Jenkin *et al.*, 2016).

So, what is a DES?

Firstly, we need to understand what we mean by a eutectic mixture. Figure 1 illustrates a simple binary eutectic mixture. Here we have two components, A and B. The potential compositions of mixtures between A and B are plotted against their melting points. The melting points of pure A and B are indicated on the opposite axes. As the composition of the A+B mixture is changed so too is the resultant melting point. At the eutectic composition the melting point is lowest for the mixture. A very common example of an important eutectic mixture is that of salt and ice. When added together they form a eutectic mixture that is composed of 23% salt and 77% ice with a freezing point of −21 °C.

What is important is that DES melt at far lower temperatures than their component chemicals. For example, urea has a melting point of 133 °C and choline chloride's melting point is 302 °C, yet when mixed in their eutectic composition the mixture melts at 12 °C.

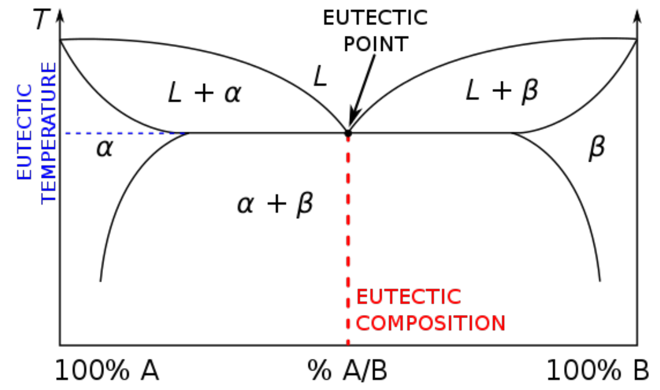

Figure 1 A schematic representation of a binary eutectic formed between components A and B; note the eutectic melting point is considerably lower than either pure substance melting point;
https://en.wikipedia.org/wiki/File:Eutectic_system_phase_diagram.svg

Very promising research has been focused upon the effectiveness of DES in the extraction of a wide range of metals from E-waste and minerals (Hsu *et al.*, 2019; Hartley *et al.*, 2022). The recovery of 'waste' E-metals from computer components is only one way DES have been utilised. Research has shown them to be highly effective catalysts, both for abiotic and biological processes (Ünlü, Arıkaya and Takaç, 2019), electrodeposition and electropolishing (Abbott *et al.*, 2015; Barzinjy, 2016), the production of Al-based and redox-flow batteries (Padwal *et al.*, 2022) and in carbon-capture technologies (Osman *et al.*, 2021).

The DES process

Figure 2 provides illustrations of the process used by the Leicester team and clearly shows the effectiveness of this approach in extracting gold from E-waste (components from a computer motherboard).

(a) Mixing together urea and choline chloride in the appropriate proportions

(b) Stirring the mixture at 50 °C for 20 minutes produces a colourless solution (DES)

(c) To this mixture an oxidising agent is added (e.g. I_2, $FeCl_3$)

(d) A strip of computer component that contains gold is dipped into the DES for 20 minutes; this is enough time for the gold to dissolve into the DES

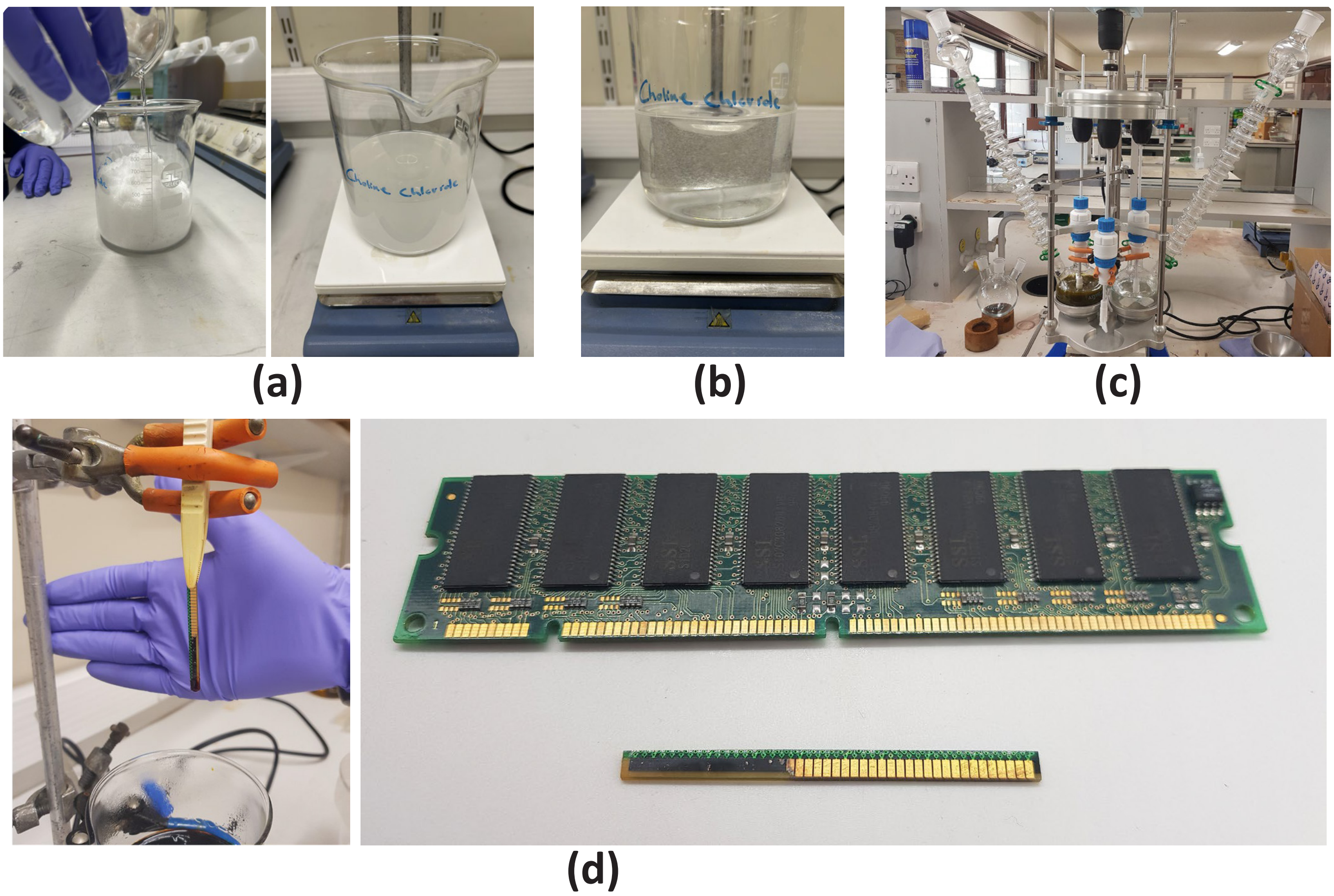

Figure 2 This series of photos illustrates the process used to extract gold metal from E-waste, in this case a computer board component (photographs: A. Markwick and E. Bulmer)

Box 1 Making a DES for dissolving copper (obtained from waste)

To dissolve copper, we will be making ethaline (a deep eutectic solvent (DES) made with choline chloride and ethylene glycol) and adding to this an oxidising agent, in this case $FeCl_3 \cdot 6H_2O$. This method will be used to make ~150 cm^3, but the amounts can be changed to reflect the needs of the experiment.

Method for making the DES

1 Weigh out 80 g of choline chloride in a beaker. Add a magnetic stir bar to the beaker.
2 Calculate the number of moles of choline chloride from the weight. Based on a 2:1 ethylene glycol:choline chloride molar ratio, calculate the amount of ethylene glycol needed. Using 80 g of choline chloride, 71.1 g of ethylene glycol is needed.
3 In a separate beaker, weigh out the desired amount of ethylene glycol.
4 Add the ethylene glycol to the choline chloride.
5 Place the beaker on a hot plate. Turn the hot plate on to ~100 °C and turn on the stirring. Wait for all the solid to dissolve, and the solution to turn into a clear and colourless liquid. This liquid will be more viscous than water. You have made the eutectic mixture.
6 In a measuring cylinder, measure out the DES needed for the experiment. Add this to a beaker.
7 Calculate how much $FeCl_3 \cdot 6H_2O$ is needed to make a 0.5 mol dm^{-3} solution and weigh it out in a weighing boat. This should be 20.3 g of $FeCl_3 \cdot 6H_20$ for 150 cm^3 of DES.
8 Add a stir bar to the beaker containing the DES and place it on a hot plate. Set the hot plate to ~100 °C and turn on the stirring.
9 Add the $FeCl_3 \cdot 6H_2O$ slowly to the beaker. Wait for it all to dissolve.

If not using immediately, the DES should be stored in a storage bottle at around 50 °C, preferably in an oven. If this is not possible, the DES needs to be heated before use as some crystals may have formed in the DES. If crystals have formed, place back on the hot plate at ~100 °C with a magnetic stirrer and heat until all crystals are dissolved.

Method for dissolving the copper

1 Take your DES solution and add ~150 cm^3 to a beaker. Add a stir bar and place the beaker on a hot plate. Raise the temperature of the solution to 80 °C (78–82 °C).
2 Once the solution is at temperature, add your waste copper wire. Depending on the thickness, it may take longer to fully dissolve.
3 After 30–40 minutes (depending on the thickness of the copper) remove from the solution and see the dissolution.

This can also be used to leach metals from ore or from electronics waste. To do this, you use the same method to make the DES but may need to adjust the concentration or type of the oxidising agent based on what you are trying to extract, and the amount of metal present in the sample. For example, if you are trying to extract nickel from nickel sulfide ore, you could use the same 0.5 mol dm^{-3} iron chloride DES, but react the solid at 80 °C for 24 hours, to take the reaction to completion. After this time, you filter the DES to separate it from the solid and then precipitate the nickel from the solution. To leach a nickel oxide, you may need a different oxidiser, such as oxalic acid, because of the difference in chemical structure and grain structure.

This method can therefore provide a source of critical metals from recycled sources, or sources from which it is otherwise uneconomical to recover the metal. It is also adaptable to the source of the metal, and to the metal itself, making it a potentially more desirable method.

Research is now underway to find the best ways to recover the metals from the DES. For example, different metals can be selectively precipitated from the DES using displacement chemistry and by employing electrochemistry. A simple method that you might like to try in the laboratory to extract copper is given in Box 1.

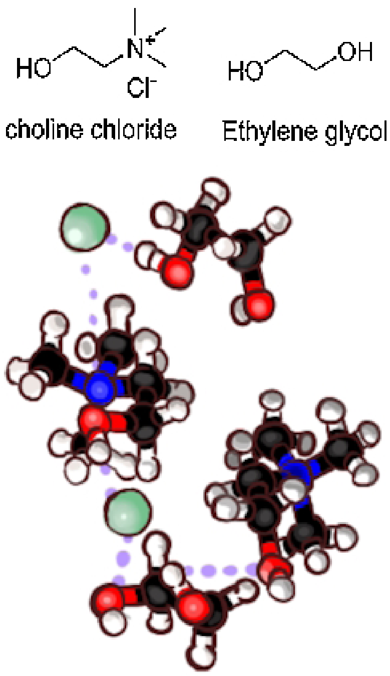

Figure 3 Structural formulae of components of ethaline (choline chloride and ethylene glycol) individually, and the proposed structure of ethaline with the interactions between chloride ions and the oxygen atoms of both choline and ethylene glycol molecules; NB. nitrogen is dark blue, oxygen is red, carbon is light blue, hydrogen is white and chloride is green; image created by Georgia Nixon

Examining the chemistry of interaction in DES

While research on DES is still in its infancy, several studies have been undertaken to explore the underlying chemistry of DES formation and the interactions with metals and their minerals that enable extraction (e.g. Arkawazi, Barzinjy and Hamad, 2021). Figure 3 shows the components of the DES ethaline (choline chloride and ethylene glycol), and the proposed structure of ethaline with the interactions between chloride ions and the oxygen atoms of both choline and ethylene glycol molecules (Arkawazi *et al*, 2021) when they are combined in the DES.

Figure 4 shows that a similar structure is also shown in the urea–choline chloride DES (Arkawazi *et al.*, 2020). Once again, the lattice is disrupted by the interactions between the chloride ions and hydrogen bond donors.

Exploiting these unique properties means metal extraction and recovery can occur with much less environmental impact. Abbott *et al.* (2015) discuss using a DES to extract gold and silver. They used 0.1 mol dm^{-3} of iodine in ethaline to simultaneously oxidise metals such as gold and silver from a sulfide-based ore and selectively remove the metals using an electrocatalytic process (a process that is able to regenerate itself through a series of redox reactions). The redox potentials calculated for the extraction of gold (Au to Au^{+}) should not have been possible. However, closer inspection revealed the iodine undergoes two redox processes that ultimately regenerated the iodine:

1 $I_2 + 2e^- \rightleftharpoons 2I^-$

2 $I_2 + I^- \rightleftharpoons I_3^-$

3 $I_3^- + 2e^- \rightleftharpoons 3I^-$

(M = metal and M^{x+} = metal ions)

In step 1, I_2 oxidises the metal to form I^- ions and M^{x+} ions. Further reaction in step 2 between I^- and I_2 yields the I_3^-, which, in step 3, then oxidises more metal to yield M^{x+} ions and I^- ions. The I^- ions then react with I_2 to generate further I_3^- ions and the process continues.

Figure 5 illustrates how Abbott *et al.* (2015) visualise the interaction and oxidation of metals in ores by the interaction with I_2. This process allows two or more metals to be oxidised at the same time, selectively depositing a metal on the cathode by electrowinning, and regenerating the iodine at the anode according to reactions 1–3.

Conclusion

These new technologies are critical for global transformation towards carbon-neutral economies and so it would be wise to invest now in adapting our current outdated science curriculum for our students. From the example of DES chemistry above, the UK's current GCSE (ages 14–16) and A-level (ages 16–18) curriculums already provide a sound foundation for understanding these processes, for example intermolecular bonding, redox, dissolution processes, thermodynamics and so on. We must now develop ways for students to apply this knowledge to explore these technologies. This is explored in more depth in Markwick, Bulmer and Smith-Barnes (2023).

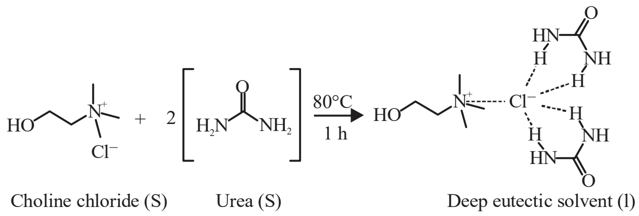

Figure 4 Proposed structure of the urea–choline chloride DES system (Arkawazi *et al.*, 2021)

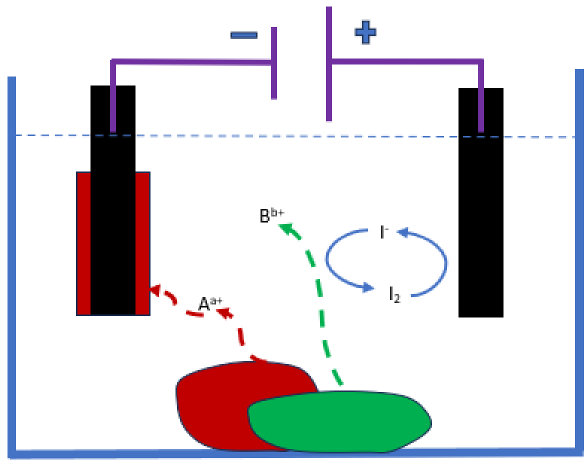

Figure 5 A simplified illustration of the oxidation and dissolution of metals (e.g. Au and Ag) by iodine; deposition of the metals at the cathode makes extraction possible (Abbott *et al.*, 2015)

A cautionary note

DES have been shown to have a relatively low environmental impact compared to current practices and to ionic liquid processes, being biodegradable and biochemically benign. However, these data are based upon small-scale use of the reagents, whereas if DES technologies become the norm for extraction and recycling metals, much larger quantities will be required and for longer time periods; under these conditions their impact upon the environment is unknown. For example, urea, which is a cheap fertilizer, can undergo biogenic and abiogenic oxidation in the soil to produce nitrates. We are aware that increased concentrations of nitrates and nitrites in the watercourse can lead to eutrophication as algae and phytoplankton levels increase and these can then form harmful toxins that enter the food chain. High levels of nitrates in our body, ingested from diet, can lead to health issues such as methemoglobinemia ('blue baby syndrome') in babies and, if converted into nitrites in adults, lead to reduced ability for haemoglobin to carry oxygen and have been linked to an increased chance of cancers such as colorectal and thyroid in adults (Ward *et al.*, 2018). We must also consider that the increased use of urea-based DES may increase the need to remove nitrates from drinking water, which is a high-energy and costly process (Matei and Racoviteanu, 2021). However, research has shown that there are many combinations of reagents that can form useful DES (Smith *et al.*, 2014) and so use of such chemicals as urea might be avoided or at least limited.

On balance, it seems that the application of DES for extraction and recycling metals is a remarkable step forward in the search for greener technologies and hopefully a cleaner and healthier planet.

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Unpacking procedural and conceptual difficulties of grade 13 students in solving problems in genetics crosses

Sheyne Moodelly, Michael J. Reiss and Anwar Rumjaun

Abstract This study examines the procedural and conceptual difficulties experienced by biology students when solving genetics cross problems related to inheritance. A qualitative case study was used and data were gathered from grade 13 (age 18) biology students in Mauritius. Initially, students who engaged in four problem-solving exercises were observed and their work was collected and analysed to elucidate their procedural difficulties. Then, individual semi-structured interviews were undertaken with the students. The results show that most students found it difficult to connect the various levels at which genetics can be understood (molecular, microscopic, macroscopic and symbolic). This severely hampered their understanding of genetics and their ability to answer correctly questions to do with genetics crosses. Suggestions are made as to how this might be remedied.

Understanding genetics crosses is a well-established problem (Dougherty *et al.*, 2011). Although familiarisation with genetic information may allow students to solve genetics crosses, being able to solve such crosses can nevertheless go hand in hand with an incomplete knowledge of inheritance because the genetics diagrams employed in solving genetics crosses do not on their own show the patterns in gene transmission.

For a good understanding, students must move to the abstract level of genetics. Unfortunately, the complexity inherent in understanding genetics can lead to students rote learning or unthinkingly applying rules they have learnt. To solve problems in genetics, students need to understand the relevant theory, which necessitates a degree of comprehension that is organised into interrelated levels associated with various subject disciplines, including biology, biochemistry and mathematics.

There are four interrelated levels of knowledge involved in learning genetics (Figure 1), namely molecular (biochemical), microscopic (cellular), macroscopic (organisational) and symbolic (representational) (Chu and Reid, 2012). Some students may cope well with a particular level but experience major concerns with another. This study explores the extent to which students are acquainted with the various levels and their challenges.

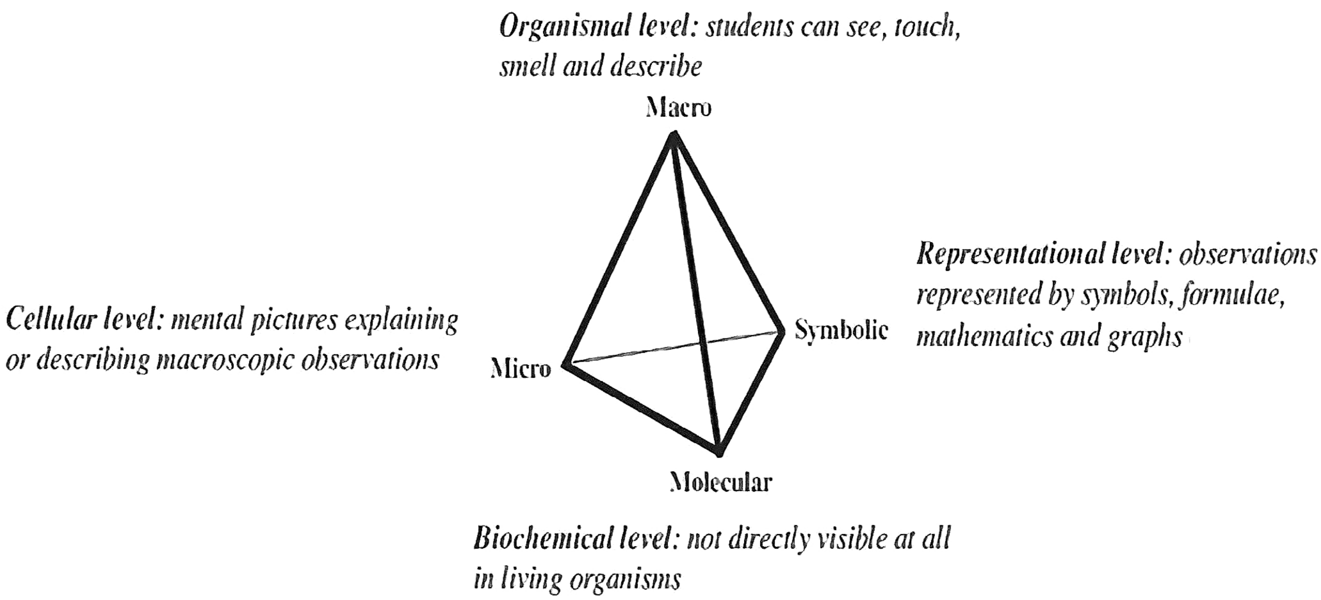

Figure 1 The four levels at which genetics can be learnt (Chu and Reid, 2012: 287)

Methodology

A descriptive case study was adopted to investigate the difficulties experienced by grade 13 (A-level, age 18) biology students in Mauritius when attempting to solve genetics problems. A private, secondary, non-fee-paying school was selected, partly on the grounds of ease of access. The students were in the science stream, and so also learning chemistry and mathematics, and consisted of boys and girls. These students had been studying biology from their early years of secondary schooling and had passed their grade 11 national examinations (Cambridge O-level). They had been taught about simple monohybrid inheritance and the relationship of meiosis to gamete formation. Purposive sampling was used, consisting of eight grade 13 biology students who volunteered for the study. A mix of low-, medium- and high-performing students, based on their results on past tests and written examinations, were selected as participants. Two sources of qualitative evidence (problem-solving exercises and interviews) were used. Genetics is a biology topic that is presented quite similarly at upper high school level in many countries, so our findings are likely to be widely applicable.

Data were collected in two stages. During the first stage, the participants had to solve four genetics crosses and show the inheritance patterns of particular traits. Participants' worksheets were collected and their procedural steps, adapted from Cambridge International AS and A-level Biology 9700 syllabus for 2019–2021, were examined. The second stage consisted of semi-structured, one-to-one interviews. An inductive analysis was used because of its flexibility and ability to provide a rich description of the problem phenomena. The study complied with the ethical guidance in BERA (2018).

Results

Procedural difficulties

The first stage of the study focused on the students' abilities to use the appropriate procedural steps while attempting to solve four genetics crosses. One major procedural difficulty is the construction of an appropriate symbolic key, which constitutes the first step of the problem-solving exercise. These difficulties are summarised in Table 1.

The first procedural step is for students to identify parental phenotypes and genotypes. Most students encountered difficulties in problem four. This was mainly attributed to the inappropriate use of superscripts (for example, X^h correctly indicates that an X chromosome carries the allele for haemophilia and X^H that an X chromosome carries the normal allele, whereas the Y chromosome does not have the gene in question and so at this locus cannot be represented with superscripts). It was also found that the use of superscripts in X-linked inheritance further confused students when constructing the required symbolic key in codominance. For example, student S8 did not use a superscript to represent the codominance allele because they thought that superscripts are only used in X-linked inheritance. Furthermore, it was found that the construction of a symbolic key for X-linkage, representation of a carrier female and X-linkage disease among males were seen to be the most challenging tasks. For example, the response of S3 indicated that the difficulties in using the required symbolic key during X-linkage disease are due to confusion about which X chromosome carries the dominant allele. Hence, S3 incorrectly represented a carrier mother as having two dominant alleles and incorrectly indicated that a Y chromosome had a recessive allele.

The second procedural step was the representation of genetics concepts and processes. Many problems encountered in this step originated from the mistakes that students had committed during the first step. For example, a mistake in determining the parental genotypes correlated with an incorrect symbolic key to alleles. Mistakes were more evident for dihybrid and X-linkage problems. Furthermore, even though some students had been able to generate the correct parental genotypes, they produced incorrect gamete combinations. It was found

Table 1 Student difficulties with symbolic representation

Problem	Difficulties	Student code
One	Inappropriate use of the symbol to represent the recessive allele.	S6
Two	C^{RW} is an incorrect symbolic key for roan (codominance).	S2
	Allele should be represented as superscript instead of capital 'R' (student uses RR instead of C^RC^R).	S8
Three	Inability to construct a symbolic key for dihybrid inheritance.	S2, S7
Four	Some students represented X-linkage inheritance as a simple autosomal inheritance. They did not use the symbol 'X'.	S3, S5

that several of the students simply rote-learnt the procedural steps and 'solved' the genetics problem in a non-meaningful fashion. These students seemed to have a poor understanding of allele segregation and independent assortment, something that was confirmed during the interviews with them. Most of the students were able to apply the first three procedural steps during simple monohybrid and codominance crosses, but, in dihybrid crosses, although approximately half the students correctly identified the parental genotypes and phenotypes, few correctly represented the gametes. In X-linked inheritance, few students correctly identified the parental genotypes and phenotypes. However, many students were able to proceed to the next (third) step to represent gamete formation and the genetics cross. This indicated a form of rote learning of the procedural steps. The representation of gametes in a dihybrid cross and portraying the parental genotype using appropriate alleles in X-linkage inheritance were the most problematic tasks. These difficulties are highlighted in Table 2.

The final (fourth) procedural step was to show the offspring genotypes and phenotypes. Problems one(b), two and four(a) required the students to perform simple inheritance forward problem-solving. Seven of the students correctly identified the offspring genotype and phenotype for problem one, six did so for problem two, four did so for problem four, but none for problem three. Regarding the offspring, seven students correctly showed the genotypic ratio for problem one but none for any of the other three problems; furthermore, concerning the phenotypic ratio, five students were correct for problem one, two for problem two, and none for problems three or four. It seemed that when students reached the end of the problem-solving exercises, they tended to omit the offspring genotypic and phenotypic ratios.

Table 3 Number of students successfully reaching an answer in the last procedural step

Problem	Correct identification of:	
	Offspring genotype and phenotype	Offspring genotypic ratio
One	7	7
Two	6	0
Three	0	0
Four	4	0

Problem one(c) and four(b) required backward problem-solving. Most students correctly stated the genotype of the parents for problem one(c) (an autosomal monohybrid cross). However, for problem four(b) (X-linked inheritance), only one student correctly solved and explained the result, despite all the students having been taught previously about X-linked inheritance. The other students either provided a genetics diagram without any explanation (suggesting rote learning) or provided only a partial explanation. S2 correctly drew the

Table 2 Difficulties in representing genetics concepts and processes

Problem	Difficulties	Student code
One	Terminology misunderstood: • One parent is heterozygous for black eyes, thus cannot be represented as 'BB'. • Confusion between genotype and phenotype.	 S6 S1
	Shows only one gamete produced from a parent instead of two.	S1
	Genetics cross not drawn to demonstrate fertilisation.	S1
Two	Genotype for roan colour coat wrongly represented. However, most procedural steps were represented [students had previously been taught what 'roan' means].	S2, S8
Three	Wrong allele combination during gamete formation. However, correct parental genotypes were shown and Punnett square appropriately used.	S5
	Terminology misunderstood – heterozygote animal for grey fur and long tail cannot be represented as 'GgTT'. Both traits should be in the heterozygous condition (GgTt).	S2
	Shows only one gamete for pure-bred parent instead of four.	S1, S2
	Failed to construct a Punnett square, although parental genotype and gamete formation correctly identified.	S7
	Represented parental genotype as gametes and gametes as F1 generation. However, Punnett square correctly used.	S8
Four	Since the disease is X-linked, the Y chromosome in a male cannot carry or be represented with an allele.	S3

genetics diagram for problem four(b) but failed to state the maternal genotype, as specified in the question. It seems likely that S2 had simply rote-learnt the steps for providing a genetics diagram without having a meaningful understanding of the process behind it.

S5 considered the mother to be 'homozygous recessive', which is wrong because, in the case of haemophilia, this combination is (almost always) lethal for females. On the other hand, S7 correctly drew the genetics diagram and the parental genotypes were well identified.

The above findings demonstrate that the majority of the students failed to use all the required procedural steps when attempting to solve the genetics problems. Most students managed to solve the monohybrid and codominance crosses, which was unsurprising as both involved only simple autosomal inheritance. Some students correctly solved the genetics crosses but lacked certain procedural steps. However, no students were able to solve the dihybrid cross correctly using all procedural steps, despite having been introduced previously to dihybrid crosses; typically, they failed to show the correct possibilities for the gamete combinations. Regarding the X-linkage problem, students were more likely to be unsuccessful than successful.

Conceptual difficulties

The second stage of our research builds on the first and seeks to understand students' conceptual difficulties about their genetics reasoning through semi-structured interviews. The interviews enabled additional questions to be posed, based on the student problem-solving exercises and responses. The key findings from the interviews are summarised in Table 4.

One major conceptual challenge was that some students only partially understood key genetics concepts, as highlighted in Table 5. Although the majority of students understood the process of meiosis and that it results in gamete formation, four of the students were unable to identify on their genetics diagrams where meiosis took place. Two of the students correctly referred to gametes as sex cells and identified them as haploid, but six associated the formation of gametes with the fusion of two alleles. On further probing during the interview, it seemed that students confused gamete formation with fertilisation. Six of the students correctly described the process of fertilisation. However, when asked what the cross lines drawn on their genetics diagrams (which result in the F1 generation) represented, only two of the students correctly referred to fertilisation. Two referred to meiosis and the other four only to the fusion of gametes. This demonstrates that most students had a poor understanding of these key genetics concepts and this impacted on their ability to relate these concepts to their solution process. A related difficulty was students' variable understanding of genetics terminology.

Overall, the findings indicate that the inability of most of the students to use the correct procedural steps is probably the result of rote learning and a lack of conceptual understanding of key genetics concepts, and their inability to relate these concepts to their problem-solving exercises.

Discussion

For a better comprehension of genetic phenomena, students must be able to understand the interconnections among four levels, namely the microscopic, symbolic, macroscopic and molecular levels (Chu and Reid, 2012). Similarly, Mussard and Reiss (2022) highlighted that learners of genetics need to reason between these levels. Figure 2 provides an example of a student's successful response to question 1a: '*Choose suitable symbols for these alleles, and then draw a monohybrid genetic diagram to show the probable results of a cross between a heterozygous parent and a homozygous recessive parent. Clearly write the proper labelling at each step*'. On Figure 2 we have added, in boxes, information about the four

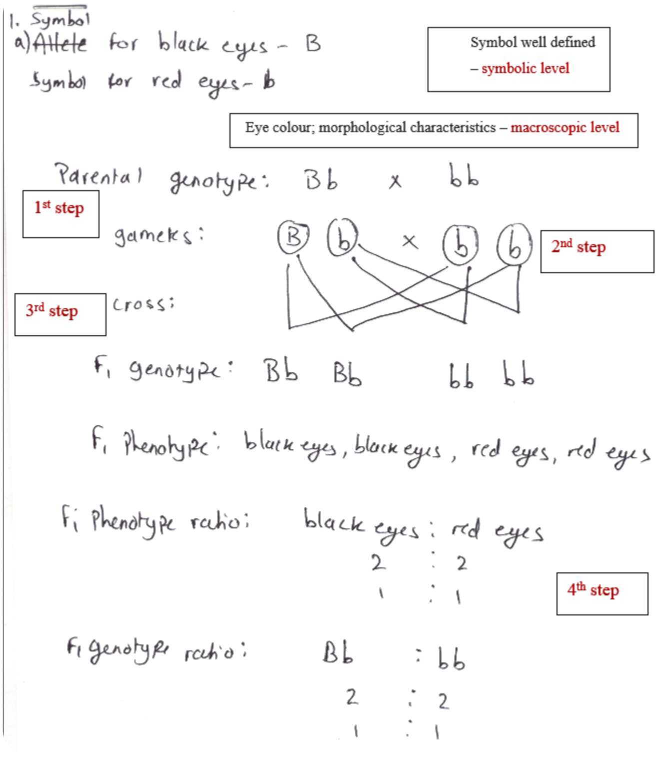

Figure 2 An example of a student's answer to a genetics problem that successfully uses the four procedural steps identified and makes clear reference to the symbolic and macroscopic levels

Table 4 Main conceptual difficulties as revealed through interviews

Conceptual challenges	Difficulties encountered
Lack of meaningful solutions	Four students were confused or had a poor understanding of genetic concepts and could not relate these concepts appropriately to their problem-solving solution. For example, many students did not understand what a gamete is and were not able to represent its formation on the genetics diagram. Additionally, students did not understand the concept of 'pure-bred' and were unable to represent this using the appropriate symbol.
Poor understanding of key genetics concepts	Confusing gamete formation with fertilisation.
	Seemed to have learnt genetics concepts separately from genetics diagrams.
Misunderstanding of terminology	Use of gene and allele interchangeably.
	Many students associated pure-bred with homozygous dominant traits.
	Some students were hesitant when trying to answer certain interview questions or were confused about the use of the appropriate genetics terms.
Difficulties in understanding X-linked inheritance	Seemed not to understand that males have only one X chromosome, and so a recessive allele would cause the disease in males.
	Treat X-link inheritance as autosomal.

Table 5 Students' responses to key genetics concepts

Genetics concept	Student responses during interview	No. of students
Allele	Different/alternative form of a gene [good understanding].	2
	Associate it with a chromosome – found on a chromosome.	2
	Relate to the formation of genotype or contain the dominant or non-dominant characteristics.	2
Gene	Section of DNA coding for a specific character in the body [good understanding].	2
	Found on DNA.	4
	Give specific characters, such as eye colour.	2
Is a gene a protein?	No [good understanding].	2
	Yes.	4
	No idea.	2
Composition of gene	Nucleotide [good understanding].	2
	Amino acid.	2
	No idea.	4
Pure-bred	Only one student understood this term and identified it as 'not in heterozygous condition but in homozygous which can be either dominant or recessive' [good understanding].	1
	The majority considered pure-bred as a condition in 'the homozygous dominant' state.	7
Carrier	Carry/transmit the disease but do not show any sign of illness [good understanding].	4
	Carry a faulty gene/allele.	2
	Carry one recessive allele for the disease.	2
Genotype and phenotype	Identified genotype as the allele the individual possesses and phenotype as the physical appearance of the individual [good understanding].	8

procedural steps and the symbolic and macroscopic levels.

When attempting to solve a genetics cross, the first procedural step requires the construction of a symbolic key. Confusions in symbolic representation can arise because of the different symbol systems. Each symbol system follows its code; thus, students are compelled to learn how to translate these symbols before attempting the problem-solving exercises, which may lead to mental overload. Cognitive conflict can arise in students when there is a shift from one representation system to another. For example, students may correctly use a symbolic key for monohybrid inheritance but have difficulties with dihybrid crosses and X-linked inheritance which require different symbolic representation.

A poor understanding of the relationship between sexual reproduction and the mechanisms of genetic inheritance may hinder students' ability to relate biological phenomena to what they have learnt in genetics. However, once a student can use relevant prior knowledge and apply it to what they are learning from their genetics curriculum, their mental framework will trigger a succession of changes that will modify existing concepts and provide links with older ones. When rote learning takes place, students may assimilate a new concept and add it to their cognitive structure without the new concept interacting with existing knowledge. Learning concepts as isolated entities may result in a dearth of logical meaningfulness in a student's cognitive structures and shortcomings in their understanding of genetics (Cavallo, 1996). When students can solve simple inheritance problems with reasonable competence but have difficulties with dihybrid and X-linked inheritance, this shows that they may possess domain-specific knowledge but lack domain-general knowledge. Students would be likely to benefit, before tackling these harder problems on their own, by being explicitly instructed through the use of worked examples.

The symbolic level can often bridge the macroscopic and microscopic levels. Whereas the microscopic and symbolic levels can be fairly readily addressed during teaching, the macroscopic level can perhaps best be taught by the representation of phenotypes through breeding experiments (e.g. of *Drosophila*), which are not usually undertaken in Mauritian schools. Because of limited resources and time constrains, the macroscopic level is, perhaps surprisingly, the least considered of the four genetics levels at the Mauritian secondary school level. Consequently, in future curriculum planning, new teaching strategies, such as practical work with ears of corn and the use of animations or simulations, could be used to portray experimentation at the macroscopic level, helping students to relate what happens at other levels to what happens at the macroscopic level.

Problem-solving in genetics and inheritance should be well organised in a stepwise manner. These procedural steps include: representing the alleles using symbolic keys; defining parental phenotypes and genotypes; showing how alleles segregate to form gametes; making the cross to show how the alleles assort independently to form new combinations among offspring; and determining the genotypic and phenotypic ratio of the offspring (F1 generation).

As found in some other studies, students were confused about different levels of organisation and tended to explain a particular biological phenomenon at only one level, failing to interrelate concepts on different levels, which Verhoeff (2003) characterised as a lack of vertical coherence. A vertical alignment of the biology curriculum should enable the gradual development of students' knowledge, building on preceding learning encounters, and this may foster a positive learning experience in genetics. Students' misconceptions at a particular level can affect their understanding at other levels. For example, some students cannot explain how an allele for colour-blindness (in X-linked inheritance) can be passed from a mother to one of her children, with the result that a son may be colour-blind, even though the trait appears in neither parent. These difficulties arise because traits manifest at the macroscopic level, whereas genes are at the microscopic level, and genotypes at the symbolic level. It seems likely that students would benefit from their teachers making such links explicit.

Students in this study often associated genes with amino acids instead of with nucleic acids. The interviews revealed that this misconception could be attributed to the fact that for these students a gene contains a code to synthesise a protein, and a protein is made of amino acids. Moreover, most molecular structures in living things are not directly visible. Consequently, most molecules must be imagined by students. Genetics is a challenging topic, in part due to its microscopic entities. Visualisation using genetics diagrams can help to make the microscopic world 'tangible'. However, many students solved genetics cross problems with little scientific knowledge of cell division. They were unable to relate chromosome segregation to the independent assortment of alleles, and did not appreciate how meiosis leads to gamete formation. This shows that students are often not able to refer to the requisite biological knowledge to solve problems in new situations. This could also help explain why many students could not think critically and draw from prior knowledge to solve genetics problems.

Conclusions

The complexity of inherited changes has to do with a comprehension of genetics that necessitates 'to-and-fro' thinking between the four levels of organisation, namely the microscopic, symbolic, macroscopic and molecular (Chu, 2008). However, each level has its degree of complexity (Chu, 2008), with the symbolic level being a representation, using letters or other symbols. It is known that confusion may arise in students' minds from using several symbol systems simultaneously (Gilbert, 2005). As revealed by this study, if students are not familiar with these symbolic representations, they may encounter challenges in visualising what is happening at the microscopic level and in explaining their problem-solving procedures. As a result, students not infrequently have difficulty connecting conceptual knowledge at the microscopic level to phenotypes (at the macroscopic level).

This case study demonstrates that many students tend to rote-learn the procedural steps and may reach a correct solution to a genetics problem but are unable to apply the appropriate genetics concepts, especially with respect to sex-linked inheritance. This may be due to the fact that the Mauritian educational system is mainly examination-centred, catering mostly for students' achievement in terms of grades, rather than identifying whether learning with understanding is occurring. Furthermore, the actual biology curriculum at A-level does not require students to navigate across the four levels of organisation and develop their understanding of the terminology and concepts involved in genetics. We would argue that such navigation should be specified in the curriculum to help students obtain a better understanding of genetics.

Finally, it was noteworthy that in the problems used in this study, little reference was made to the molecular level. With so much of genetics nowadays requiring an understanding of molecular biology, this finding is significant; a lack of conceptual understanding by students at this level adversely impacts their ability to develop a sound understanding of genetics.

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Scientific language: how important should it be to teachers of science?

James D. Williams

Abstract Scientific words are seen by some as a barrier to learning. Language is the dominant medium of human communication, both spoken and written, and is an integral part of any society. As a means of developing shared understandings and culture, language has a crucial role to play. Language also plays an important role in developing scientific understanding. The language of science has developed over centuries and its use as a means of communicating between scientists and as a means of organising scientific thought (e.g. through the establishment of systematic names for plants, animals and units of measurement) is an important aspect of how science is viewed by non-scientists – as a technical, precise discipline that avoids personal feelings or attitudes. This article articulates some of the issues with scientific language and argues that more attention to scientific language can increase scientific literacy overall.

Scientific words and terminology are seen by some as a barrier to learning (Fang, 2006). Given that the dominant form of communication within science lessons in schools is language based, including the written word, this could be problematic. Kramsch and Widdowson (1998) show that language has a crucial role to play in developing shared understandings and culture. An aim of any subject education would be to have shared understandings of concepts and an understanding of the cultural significance of that subject, so the language specific to any subject is important.

Several authors have commented on the important role that language has in developing scientific understanding (Lemke, 1990; Wellington and Osborne, 2001; Gyllenpalm, Wickman and Holmgren, 2010; Snow, 2010; Webb, 2010; Carlsen, 2013; van Driel, Slot, and Bakker, 2018). How science is perceived by non-scientists, that is, as a technical, precise discipline that avoids introducing personal feelings or attitudes, creates a vision of science that does not match the reality of how science actually 'is' in real life (Crosland, 2006).

This article explores the purpose of scientific language and the difficulty it presents, and explores the need for common understanding of scientific terminology by teachers and science communicators. It concludes that there is a need to differentiate key terminology within science, with the use of the prefix 'scientific' for commonly misunderstood words that have a vernacular meaning. It further concludes that the implications of not addressing the language of science through our teaching is that achieving scientific literacy for children and others will be that much more difficult.

The purpose of scientific language

A goal of scientific language, according to Reeves (2005), is to be free of connotations that reflect or create cultural bias and emotional attachment, demonstrating again a departure from the early writings of philosophers (scientists). The use of metaphor in scientific writing was criticised historically by scientists and philosophers of science (Taylor and Dewsbury, 2018), but, as Kent (1958: 185) reported, in scientific practice vagueness is constantly present:

> *Historical facts show that the meanings of words, in scientific as well as non-scientific language, are always flexible, never precisely precise, always somewhat vague, always changing … words have precise meanings only from the limited viewpoint of a fixed now and a single user.*

For writers such as Kent, the goalposts of precision in the meanings of scientific vocabularies are ever shifting. Halliday (2004) contends that more troublesome than the actual words used in science is the grammar of scientific writing. The idea that the vocabulary of science is the source of difficulty in learning science is more about the way in which teachers place importance on the vocabulary rather than the grammar of scientific writing. He goes on to describe seven characteristic difficulties of scientific English:

1. Interlocking definitions
2. Technical taxonomies
3. Special expressions
4. Lexical density

5 Syntactic ambiguity
6 Grammatical metaphor
7 Semantic discontinuity.

Halliday's position echoes that of Cassels and Johnstone (1985) who investigated high school students' understanding of 95 technical terms in science that they determined to be 'troublesome'. They concluded that the problems in understanding scientific writing lay not in the use of the technical terms (which measured as a small percentage of the text as a whole), but in how English is used in a scientific context.

Reading Halliday, and Cassels and Johnstone, it is easy to assume that technical terms and definitions are less important than the surrounding prose. The non-technical words and the way in which connectives are often used in scientific writing do, it seems, pose significant problems. Perhaps more worrying, is the confusion that can occur when technical, scientific terms also have specific as well as vernacular meanings. Reeves (2005) describes three problems that occur with the use of scientific terminology:

- The definition of the same term in different ways by scientists from different sub-fields of science.
- The use of vague terms, which can result in different definitions of those terms by different people.
- The use of inappropriate terms in scientific language.

Is there a 'common understanding' for scientific terminology?

Do all science teachers and communicators have a common understanding of key scientific terminology? For certain aspects of science, such as the definition of an atom, or the process called photosynthesis, it is reasonable to assume that there is a general, common understanding that is demonstrated through the textbooks and examination specifications. A concept such as photosynthesis will have ascribed to it a general meaning for the purposes of school science. For example, a definition I have used with children and adults is that, '*photosynthesis is the process where green plants convert carbon dioxide into useful carbohydrates (sugars) using energy from sunlight, and produce oxygen as a waste by-product*'.

Many scientific words are derived from Latin, Greek and Arabic roots. In some instances, scientific words and terminology utilise and conjoin Latin and Greek to produce a hybrid word, for example acidophile from the Latin '*ascere*' meaning sour and the Greek '*phil*' meaning love, acidophiles being organisms that prefer an acidic environment to thrive. Such hybridisation is not restricted to scientific language. Technical, but now everyday, terminology can also hybridise words; for example, the term 'television' is a combination of the Greek '*tele*' meaning 'far off' or 'at a distance' and the Latin '*vis*' meaning 'see', in the form of 'vision'. In some instances, there is no derivation from another language but a transliteration (the transposition of one word into another) such as the Greek word *amoibe* (change) to the more modern Latin *amoeba*, which also means 'to change', as the name of the single-celled organism that most people will be familiar with in their studies of biology. The shape of the cell constantly changes.

The etymology of scientific terminology is a large and complex field and beyond the scope of discussion here. Classic texts such as those by Nybakken (1994), which looks at the Greek and Latin roots of scientific words, and Brown (2000), who produced a guide for the formulation of scientific terms, reveal something of the complexities and structure of terminology. A useful, but long-out-of-print, dictionary of scientific words and meanings (Flood, 1960) is a very illuminating book that uncovers much of the mystery of scientific terminology. However, in all these books and academic treatments of scientific terminology, there is still an absence of attention to some of the more basic terms that science uses, such as, theory, hypothesis, law, principle, fact. This absence may indicate that there exists an implicit understanding of the terms when used in science or in scientific writing, such that they need no formal definition for scientists.

In simplifying scientific terms or using terminology that may also have a vernacular or common meaning, there is a danger of propagating misconceptions or creating new misconceptions. For example, a simple misconception, often cited as a refutation of evolution, is that evolution is 'just' a theory. This stems from the misunderstanding of what the term theory means in a scientific sense rather than how theory is used in a more general sense. Gould (1981: 34) addressed this misconception in an essay for *Discover* magazine:

> *In the American vernacular, 'theory' often means 'imperfect fact'— part of a hierarchy of confidence running downhill from fact to theory to hypothesis to guess. Thus, creationists can (and do) argue: evolution is 'only' a theory, and intense debate now rages about many aspects of the theory. If evolution is less than a fact, and scientists can't even make up their minds about the theory, then what confidence can we have in it?*

The misconception is further compounded as it is woven into a misconceived idea about the nature of science (NoS) and how science operates (often, mischaracterised as 'the' scientific method). As Gould shows above, there is a complex misunderstanding of not only the definition of a theory in a scientific sense, but also the idea that there is a hierarchy of stages in scientific discovery that leads to something, when 'proven', becoming a law. These misconceptions all involve language.

It would be reasonable to assume that scientists, when using such terminology, would not suffer from such misunderstandings and misconceptions but that is not necessarily the case. As Williams (2013) demonstrated, graduate scientists, training to be science teachers, from across the science disciplines also struggle to concisely, and accurately, define key terminology, such as theory, fact, law and so on, in a scientific context. Interestingly, the research found that hypothesis was the best and most consistently correctly defined term, probably due to the emphasis put on hypothesis testing early in the school curriculum.

Gregory (2008: 46) also wrote on the issue of the language of science where he described the idea that some terms and items within science have '*multiple descriptors*' arising from a '*history of linguistic hybridization ... most technically complex professions exhibit a plethora of neologisms and jargon that can be all but impenetrable to nonexperts*'.

When we locate this in the practice of science education, we must do some preparatory work to ensure that the language is not 'impenetrable' or the understanding derailed by the use of scientific language. It is common for scientific texts for children to contain a glossary of terminology in a bid to ensure that unusual or uncommon terminology is clearly defined. These tend to focus on language that is either technical (covering processes) or specific to the content (perhaps the names of species). What is less common is for more widely (and commonly used) terms to be included. As noted above, terminology, such as 'theory', may well be assumed to be understood as the term is universal and used in everything from science to detective stories on television and in novels. The idea of the police inspector having a 'theory' about how the crime is committed, for example, reinforces the idea that a theory is just a hunch or a guess. A more accurate description of what the detective has described would be 'hypothesis', but linguistically this is less satisfactory from the point of view of a fictional story and narrative. In science, theory is used with a much more specific meaning, that is, a well-evidenced explanation of a natural phenomenon often agreed by most scientists.

Terms such a theory, fact, law, hypothesis, principle, and so on, also have another problem in that the terms can contain gradations from a pure guess to something that is 'proven' (Gregory, 2008; Williams, 2013) . Such widely differing definitions add to the complexity of communication between scientists and non-scientists. The scientist, using the term 'theory' with a specific definition, may not realise that the person they are communicating with is accepting its use, but with a different definition. These unspoken differences may cause issues further down the line when it comes to scientific understanding.

A different, but related issue, is the use of more technical terminology. These are terms and words that have no general vernacular meaning, but may be somewhat familiar to non-scientists, either from their own education in secondary or high school science or a general reading of the terms in non-scientific articles such as news reports.

The use of scientific language as word models

The teaching of science at secondary or high school level sometimes involves the communication of quite complex concepts in simplified forms. For example, photosynthesis is a common curriculum topic (as noted above). It usually involves a word equation and a chemical equation that simplify the process to a degree that children understand that plants make their own food by combining water and carbon dioxide using energy from sunlight to produce sugars and oxygen as a waste gas as set out below.

The word equation forms a 'word model' for the process of photosynthesis:

(energy from light)
carbon dioxide + water ————————> produces glucose + oxygen

The symbolic equation also provides a 'model' that is, arguably, a more scientific way of representing the process:

$$6CO_2 + 6H_2O + (\text{energy}) \rightarrow C_6H_{12}O_6 + 6O_2$$

The problem is that both equations produce a model for photosynthesis that is not 'real'. It does not fully describe the process of photosynthesis and the number of complex pathways involved. Plant biologists will confirm that further study of photosynthesis reveals many different and complex biochemical pathways in plants that result in food production and oxygen.

At secondary or high school level we rarely delve, when teaching the topic of photosynthesis, into the light and dark processes and pathways before advanced or post-16 level science. We may well gloss over the details of plant respiration, simply stating that plants do respire. In simplifying the complexity of the process, we produce a model that accomplishes the aim, that is, to help the learner to understand that plants produce oxygen, use carbon dioxide and make chemicals (carbohydrates) that are not only useful to the plant but useful to humans and many other species in the form of food.

We find similar simplifications in evolution; for example, the evolution of the horse is often portrayed as a linear progression from *Eohippus* to *Equus*, with the reduction in toes from four functional ones resulting in a single toe (hoof) in the modern horse. We may show the various stages of horse evolution by naming key animals; for example *Hyracotherium* (more commonly known as *Eohippus*) moving to *Miohippus*, then *Merychippus*, and finally *Equus*. This is also a model and not a representation of the reality of horse evolution, where species often overlapped in time.

The use of correct Latin names poses a barrier to non-scientists, who will not be familiar with the names or understand that the name may well relate to an important fact about the animal. *Eohippus* was discovered in 1876 by palaeontologist Othniel C. Marsh (1831–1899), who gave it its first Latin name, which translates as 'dawn horse'. In 1932 it was renamed *Hyracotherium* when a re-evaluation of the fossils showed it to be more closely related to the genus *Hyracotherium*. It has since been referred to by both names and, while they are used interchangeably, scientifically it should be called *Hyracotherium*. The subtlety of the re-evaluation of the description and naming of species is something the public are less aware of than practising biologists. Another example is the dinosaur *Brontosaurus*, which was renamed as *Apatosaurus* as this was its first name after discovery (Gould, 1990), the opposite of what happened with *Eohippus*.

Discussion and implications

This article covers a range of issues relating to the use of language in science. It brings together work and issues from a variety of sources, older research, aspects of the history and philosophy of science and the nature of science, and seeks to prompt science teachers to carefully consider the role of scientific language in everyday teaching. Understanding the issues raises awareness of potential sources of confusion or misunderstanding that can arise in science teaching and learning.

Scientific terminology

There is a danger that the incorrect use of scientific terminology could make the nature of science and scientific understanding inaccessible to children and others (Schwartz, 2007). This need not be the case. For all the scientific disciplines there is a need to ensure that the words we use are precisely and clearly defined to avoid misunderstanding and colloquialisms muddying the waters. If scientists present themselves as the 'owners' of complex concepts, described using terminology etymologically derived from Latin/Greek, there is a distinct possibility of alienating the people and children who may not feel comfortable using or understanding such specialist terminology. There is also a problem here in that there will be differing, competing definitions of terminology that even scientists cannot always agree on. Consistency in the use of definitions is the key outcome to strive for.

Talking science

As Wellington and Osborne (2001: 5) state, '*science teachers are (among other things) language teachers. This requires a range of strategies and skills, some of which are at a high level*'. Communication is not just language. It is a combination of visual cues, body language, and sometimes the physical act of explaining while carrying out the actual task (e.g. ecologists working in the field or demonstrating an experiment). The key is to ensure that each aspect of communication supports the concept or scientific term being discussed.

Scientific language is necessary for clear communication, but its use by science teachers has not been sufficiently researched with respect to differing definitions of key terminology. Research, for example Lemke (1990), shows that 'talking science', rather than 'talking about science', is more than just using technical vocabulary. He recommends that children are given more practice in 'talking science', shown how to combine science terms in complex sentences and encouraged to translate between scientific and colloquial statements. This last point is a key factor in increasing scientific literacy.

Conclusion

If science teachers and communicators are using variable and various definitions of key scientific terminology, this last goal of Lemke's will be very difficult to achieve. In this respect, the training that pre-service science teachers undertake should address their understanding of the nature of science as well as exploring definitions of key terms to ensure that more consistent and acceptable definitions are used in their everyday teaching. How such terms are used in the day-to-day teaching materials (e.g. textbooks and resources) should also be considered.

If a goal of science education is scientific literacy, then being able to differentiate between the use of terminology in a scientific context and an everyday context should be a core requirement of science education. Given the ease with which such terminology can and is used interchangeably, science educators should adopt a pragmatic approach to teaching children the difference between a scientific and a non-scientific theory/ fact/ law/hypothesis. Analysis of teaching materials that originate from non-scientific publications, such as newspapers, would be a useful starting point to open discussion with children on how scientists use terminology and how this differs from everyday usage.

To improve children's understanding of the special nature of some of the words used in science, the adoption of the prefix 'scientific' before such words as theory, law, fact, hypothesis, principle, and so on, to distinguish them from their common everyday use would be sensible. Adopting the prefix 'scientific' to help separate common meaning from a more precise meaning may help to reduce misunderstanding/ misconceptions and strengthen the discipline of science, as advocated by Williams (2013).

Discussion about the use of such terminology in different scientific disciplines would also be beneficial. Physicists, especially those who routinely use mathematics to model their ideas, may use the term 'theory' when, in other scientific disciplines, the word 'hypothesis' would more often be used.

Unless teachers and communicators of science and their co-workers understand the different uses of key terminology and operate with an appropriate degree of consistency in the use of definitions, then the nature of science may well continue to be misunderstood and scientific literacy will be more difficult to achieve.

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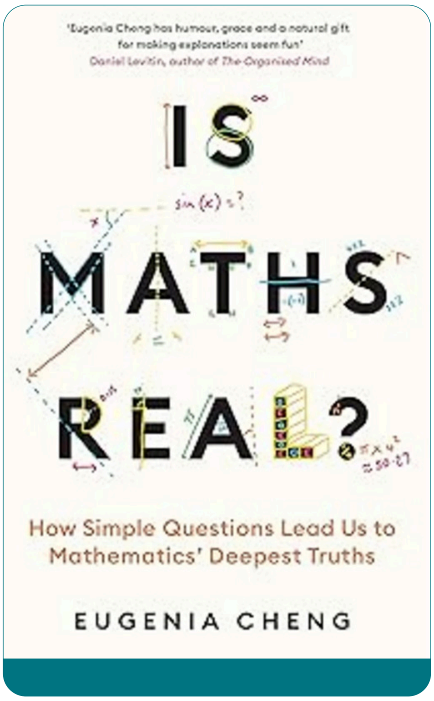


Is Maths Real?: How Simple Questions Lead Us to Mathematics' Deepest Truths

Eugenia Cheng
London: Profile Books, 2023
336 pp. £16.99
ISBN 978 1 78816952 3

This book should be read by anyone – student or teacher – with an interest in maths and should certainly be in every school library.

On the plus side, this book has inspired me to go back and re-engage with maths because, when I was studying physics, I ended up seeing it as little more than a tool. I will be reading Cheng's back catalogue. When reading this book, you can imagine the author talking directly to you. She has an incredibly accessible, engaging, entertaining and conversational style of writing. However, unlike a conversation, you cannot interject with questions or stop her for clarifications. At times, the book comes across as a stream of consciousness, though with lots of interesting asides.

For example, it never occurred to me that, by using binary, we can decorate a birthday cake for anyone up to 127 years of age by lighting a specific pattern of just seven candles. The book gives an insight into Cheng's motivation. Using a mountain as a metaphor for a mathematical problem, she is less interested in conquering the mountain than to '*shine light, clear away fog and see more clearly … to admire the view from the top*'.

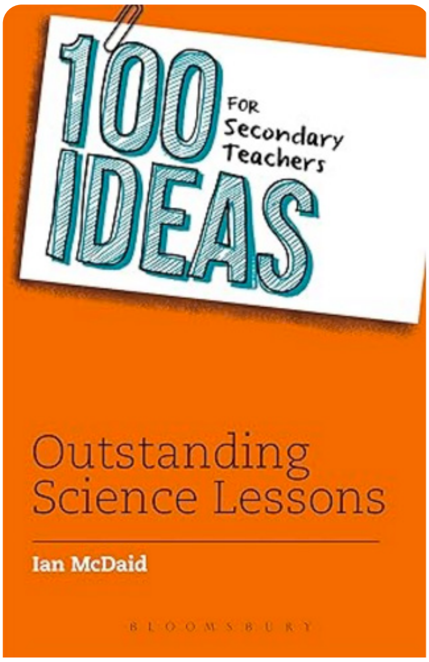
I recommend reading this book in small chunks or risk missing golden nuggets such as Cheng's explanation of how mathematical induction differs from induction in physics or philosophy. I always assumed that calculus was invented by Newton or Leibniz but apparently '*it has developed over thousands of years, from the urge to understand infinitely small things*'. She has a neat way of illustrating how a curve can be approximated by a series of straight lines.

Cheng talks about maths education and supports the use of algorithms (including mnemonics) provided it is not at the expense of gaining mathematical insight. She spends time on developing the relationship between polar and Cartesian coordinates, leading on to the sine wave, which is often obscured by the SOHCAHTOA mnemonic. She also emphasises that maths is less about getting the right answer and more about '*building good justifications*', which will resonate with teachers who repeatedly remind students to 'show your working'. However, teachers interested in maths education are advised to read *A Mathematician's Lament: How School Cheats Us Out of Our Most Fascinating and Imaginative Art Form* by Paul Lockhart.

While I agree with Cheng's social commentary, she is in danger of alienating some of her readership. She rails against the domination of maths by white European men. Perhaps she could learn something from stand-up comedians by lacing her polemic with humour, though this might not translate well to the page. The same lack of diversity afflicts science but we cannot rewrite history; we can only influence the future.

I would love to know whether maths (and science) would look different had past mathematicians and scientists been more diverse. Surely this depends on whether maths is discovered (and real) or invented and this is what I hoped the book would be about (so perhaps the title is a bit misleading?). Though she has a nice take on this question (on page 57), I was hoping for a deeper insight or a response to Max Tegmark's *Our Mathematical Universe*. Perhaps she should write one; I would certainly read it.

Mike Follows



100 Ideas for Secondary Teachers: Outstanding Science Lessons

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In *100 Ideas for Secondary Teachers*, Ian McDaid, recognised by STEM Learning as a National Expert Science Teacher, presents a series of 100 ideas, prompts and suggestions to improve science teaching and give science lessons the wow factor.

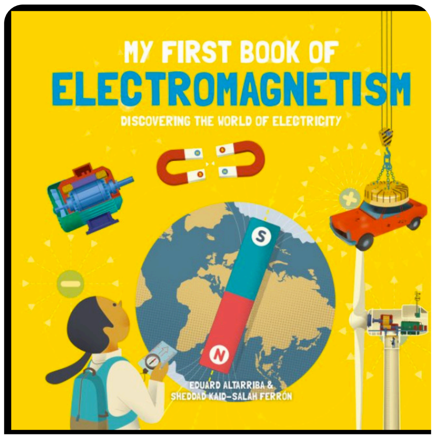
Like the other titles in the *100 Ideas* series, this book offers practical and easy-to-implement strategies and activities for the classroom. The 11 chapters cover a wide variety of topics, ranging from the big ideas in science to building relationships and dealing with Ofsted.

Each idea has a snappy title and is short and succinct, filling a single page. The rationale behind the inclusion of the idea is given along with strategies, information or ideas that can be used in the classroom. Some weblinks and video links are also provided. A typical example is Idea 16, titled '*Shock, awe and the ridiculous*', which begins by outlining the benefits of using a question hook at the start of a lesson before describing how they can be used and giving examples of shocking, awesome and ridiculous questions. My favourite was the ridiculous question '*What if all the limestone in the world turned to jelly?*' Practical work is suggested for modelling, investigative science and a few that pupils can complete themselves at home.

This is an engaging book and its approachable style and short, snappy format make it appealing to dip into on a coffee break. It is perhaps most suitable for early-career teachers as there are few new ideas here but it does successfully bring together science teaching strategies, ideas for classroom management, instructions for impactful demonstrations and suggestions for how to run classroom activities and practical work in one place. More experienced teachers may also come across some new ideas and information; I particularly liked the idea of using Lego® to build Sankey diagrams and the lists of films and clips that can be used in class, such as Lisa Simpson discovering the sex-linked chromosome that causes a loss of intelligence in the family.

Overall, this is a worthwhile book to have on your bookshelf to dip into when looking for inspiration.

Sarah Wood



My First Book of Electromagnetism

Eduard Altarriba and Sheddad Kaid-Salah Ferrón
Lewes, East Sussex: Button Books, 2022
48 pp. £9.55
ISBN 978 178708124 6

In 50 pages or so, the authors, who have produced similar books on relativity and quantum mechanics (I would love to see what they do with these subjects!), take the reader through the history of electromagnetism.

The key ideas are discussed with a light touch. Each page is filled with cartoon-style images and simple text that relates to the images, in a non-linear comic-book style. The book's informal narrative will engage the curious and keen young physicist. The proofreading by physics-trained readers has eliminated glaring physics errors.

The ideas are described and presented in a straightforward manner and there is nothing new in this book in terms of physics pedagogy. It does collect an interesting selection of key electromagnetism concepts and presents them in a fun way. This book is a quick read for younger readers rather than an exam-preparation textbook. A young reader can sit and just look at the pictures, returning to the book to study and think about the text and pictures together.

I like the experiment pages, four in total, where readers are supplied with details to perform home experiments. They are all experiments I have seen before and all will, in due course, be attempted in school physics lessons. But it is good to supply information to children who will want to try things out for themselves as home projects. The motor experiment could do with some safety information for parents to keep in mind as their children play. In fact the publisher should maybe consider this safety issue and supply a hand-out for parents managing home experiments!

This is a lively and engaging text suitable for ages 11 to 16. It is an ideal book for a science library or reference for the science classroom.

Stephen Hearn

Reviewers

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Sarah Wood teaches biology in North West London.

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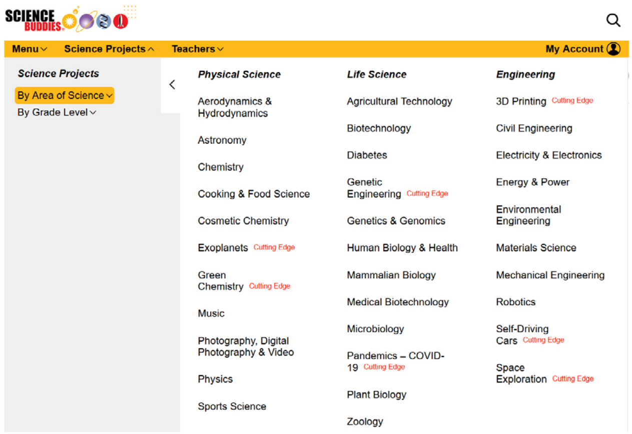
Science websearch

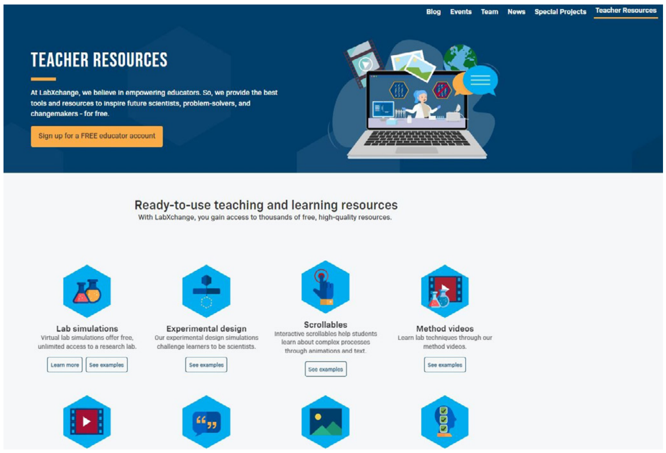
Jon Tarrant shares and reviews various science websites that may be of interest to SSR readers. See *SSR in Practice* page 38 for more website ideas.



Science Buddies

www.sciencebuddies.org

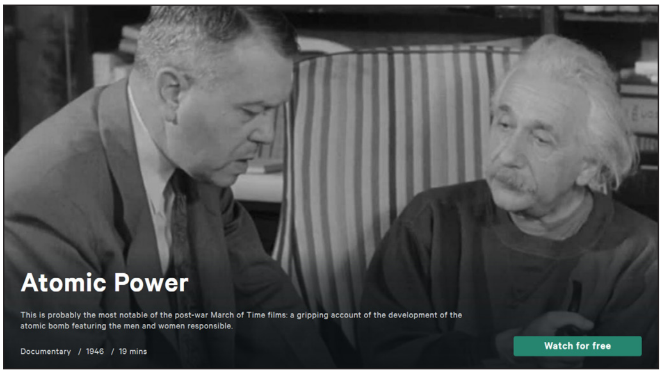
Science Buddies is a US-based charity that aims to *'inspire and educate students of all ages with hands-on STEM explorations that reflect their unique personal interests'*. The last point is particularly important as deep engagement comes from genuine interest and allowing teachers or individual students to select the most appealing project is the best way to ensure its success. The *Science Buddies* website contains a wealth of specific content from phototropism to submarines. There is also a newly added collection of video lessons with matching classroom activities, one of which explores the circulatory system by considering where a vampire might best choose to bite you. Elsewhere on the website, projects can be browsed by topic (as shown in the screen-grab above) or student age; they can also be filtered via a detailed questionnaire that highlights an appropriate selection from the 1000+ that are available. The suggestions offered when I completed the survey, using my interests as best recalled from my time as a 16- to 18-year-old student, ranged from propeller efficiency to a cellphone spectrophotometer project that inspires me even now thanks to the clarity of its explanation and the very detailed instructions provided, not to mention the ability to download free software. The project page even had suggestions for future careers related to the investigation. There are plenty of ideas aimed at chemists (including new projects for green chemistry) and yet more covering biology and medicine, from diabetes to zoology. Fresh content is constantly being added so subscribing to the free weekly newsletter is the best way to keep up with all that is new.



LabXchange

https://about.labxchange.org/teacher-resources

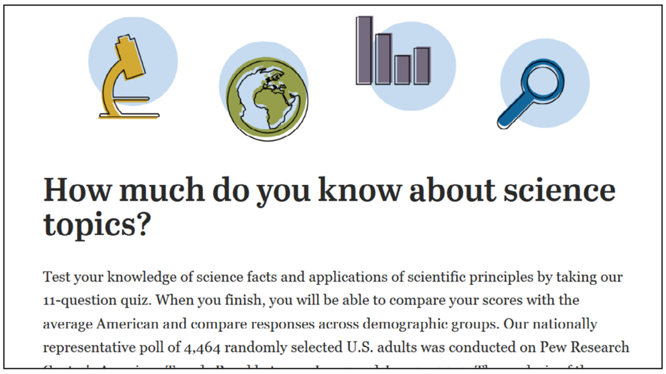
Instigated by the late Dr Robert Lue, professor of molecular and cellular biology at Harvard University, *LabXchange* offers a wealth of *'high-quality science learning experiences'*. The word *experiences* is important because, as well as stand-alone resources, the website allows educators to create (or select) pre-defined learning pathways that students can follow to develop their knowledge and understanding in a structured way. Unsurprisingly, given its founder's background, much of *LabXchange*'s own content is biological but with 150 external collaborators the full range of available resources is vast. At the time of writing there are 23,176 items available so effective indexing is clearly of paramount importance and *LabXchange* does not disappoint: applying filters for subject, resource type and language is as simple as clicking the desired radio buttons and updating is brisk. The returned links range from *PhET*, *SERP Institution* and *The Concord Consortium* simulations via *Veritasium* and *meriSTEM* videos to complete pathways from the likes of *OpenStax*, *Annenberg Learning* and *NASA* as well as *LabXchange* itself. There is even content from *Science Buddies*, reviewed above, which can be located by entering the publisher's name in the *Library* search field. Sign-up is free for both teachers and students, who must be aged 13 years or older. The only drawback to this amazing portal is how easy it is to lose sight of the *Teachers' Resources* landing page: if that happens, you can navigate your way back via the *About* link at the foot of each page.



Atomic Power

https://player.bfi.org.uk/free/film/watch-atomic-power-1946-online

With so much excitement surrounding Christopher Nolan's summer blockbuster, *Oppenheimer*, it is worth knowing that the British Film Institute has made available a much, much shorter 1946 film that features the man in person. *Atomic Power* was created as a Time–Life collaboration and includes appearances by Albert Einstein, Enrico Fermi and Lise Meitner as well as a few lines spoken by J. Robert Oppenheimer himself. The film combines archive footage with tableaux that were re-enacted for the film. Starting with the Hiroshima bombing, the content ranges from basic nuclear principles to a plutonium sample being hand-held in a boiling tube and from Einstein's atomic-bomb letter to President Roosevelt to Enrico Fermi's squash-court nuclear reactor. It culminates by reminding viewers of the importance of '*eliminating, by world agreement and for all time, the nightmare of atomic war*'. The film, which runs for just under 20 minutes, is free to watch online but I found that I needed to disable the (perhaps over-zealous) privacy protection settings in my browser before the content could be played.



Science Knowledge Quiz

www.pewresearch.org/science/quiz/science-knowledge-quiz

This is a great idea for a starter activity as it allows students to test their knowledge of science and rate their recall of facts against that of 'the average American'. The answers to most questions should be obvious for students who are doing advanced courses (aged 16+) but it is likely that the test could also be used successfully with classes aged from 14 years. There are only 11 questions so the activity should take no more than about five minutes. Owing to the fact that the next question is displayed only after the current one has been answered, I would tell the class that I am going to select the first answer every time but this is not necessarily the right response and they must record their own choices by writing the appropriate number, from one to four. It is important to keep track of the correct answers during the test because the order of the answers is randomised so the answer index varies each time. A graph showing the percentages of Americans who achieved each total score, from 1/11 to 11/11, is displayed at the end: the antacid question had the lowest success rate and only 16% of the 4464 Americans surveyed answered all eleven questions correctly.

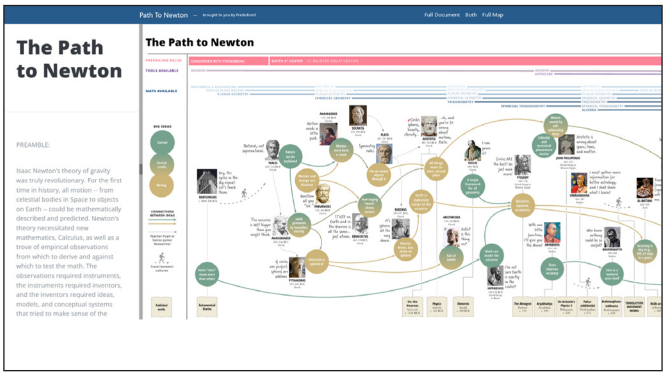
Doc Fizzix (mousetrap cars)

www.docfizzix.com

Mousetrap cars, as the name suggests, use spring-loaded mousetraps as the energy storage system to power lightweight vehicles along a predetermined course. The winner might be the car that travels the furthest or the one that completes a set distance quickest. The appearance of a PayPal-certified logo could raise suspicions of limited access but there is a lot of free content that can be used to create a classroom competition or science week activity.

Some of the free content is listed in the right-hand panel but much more is indexed on the left of the screen under the *Online Help* banner, where the first entry alone brings up more than 60 free articles to help students (and teachers) build the most successful mousetrap cars. Sadly, a lot of the pictures are missing from the step-by-step plans, and many of the weblinks are broken, but the video gallery is well stocked and there should be enough information available overall to get students started on what should be a very engaging project.

It is also worth mentioning that the *Free Physics Files* category contains a wide range of questions for assessing the knowledge and understanding of students (most likely those aged around 16 years).



The Path to Newton

www.predictionx.org/path-to-newton

According to the well-worn quote, Sir Isaac Newton attributed his scientific vision to '*standing on the shoulders of giants*'. This tribute is superbly evidenced in a detailed illustration and accompanying commentary that has been created by The Prediction Project. The work tracks '*the development of ideas about the universe and the causal mechanisms that define it across human history*'. Starting with the naked-eye astronomy of the Babylonians around 2000 BCE, the timeline shows both successful and erroneous ideas that were suggested and developed at different stages in Ancient Greece, India and the Middle East before arriving in Europe. The point, which is well made, is that Newton merely completed this work; he did not begin it. As such, this is a fantastic resource for demonstrating the evolutionary nature of science knowledge and its rich cultural background. To view the illustration in maximum detail it is best to click through to the dedicated website but there are various other resources that are worth exploring on the project's home page. Ironically, the one name missing from *The Path to Newton* is that of Robert Hooke, whose letter from Newton contained the famous 'shoulders' phrase and who expressed a qualitative link between planetary motion and a gravitational force well before it was quantified by Newton.

Today in Science History

https://todayinsci.com

Another nice starter idea is to display facts about a notable event that is linked to today's date in science history, courtesy of Ian Ellis's *Today in Science History* website. On 23 August, the events listed included the first photograph of the Earth taken from Lunar orbit (in 1966) and the filling of the first hydrogen balloon (in 1783). The balloon, designed by Jacques Charles (of gas law fame) took several days to inflate using the action of sulphuric acid on scrap iron, and was finally released on 27 August: this was more than two months after the Montgolfier brothers' (hot air) balloon but Charles's design remained aloft for four times longer and is said to have reached 3000 ft. Alongside events, *Today in Science History* also lists births and deaths and provides pages of quotations and quizzes. The website's design looks a little dated and some of its links are broken but the content is good and sources are given so that information can be checked and extended if so desired.

Jon Tarrant is a semi-retired A-level physics teacher and author/photographer based in Jersey. He is also creator of the physbang.com blog.
✉ jontarrant@cantab.net

- 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 nor checked every link.
- Sites that have been listed previously may be reviewed again to focus on new content that has been added.
- Some sites may involve subscriptions or payment for downloads. We have flagged this where appropriate.

We are always keen to learn about any websites you have found or produced that may be of interest to other *SSR* readers. Please send details of any websites you have found or produced to the *Science websearch* editor, Jon Tarrant, at jontarrant@cantab.net. We would also be interested in hearing about how you have used websites that have appeared in *Science websearch* in your educational setting.

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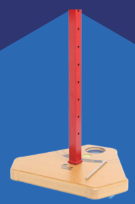

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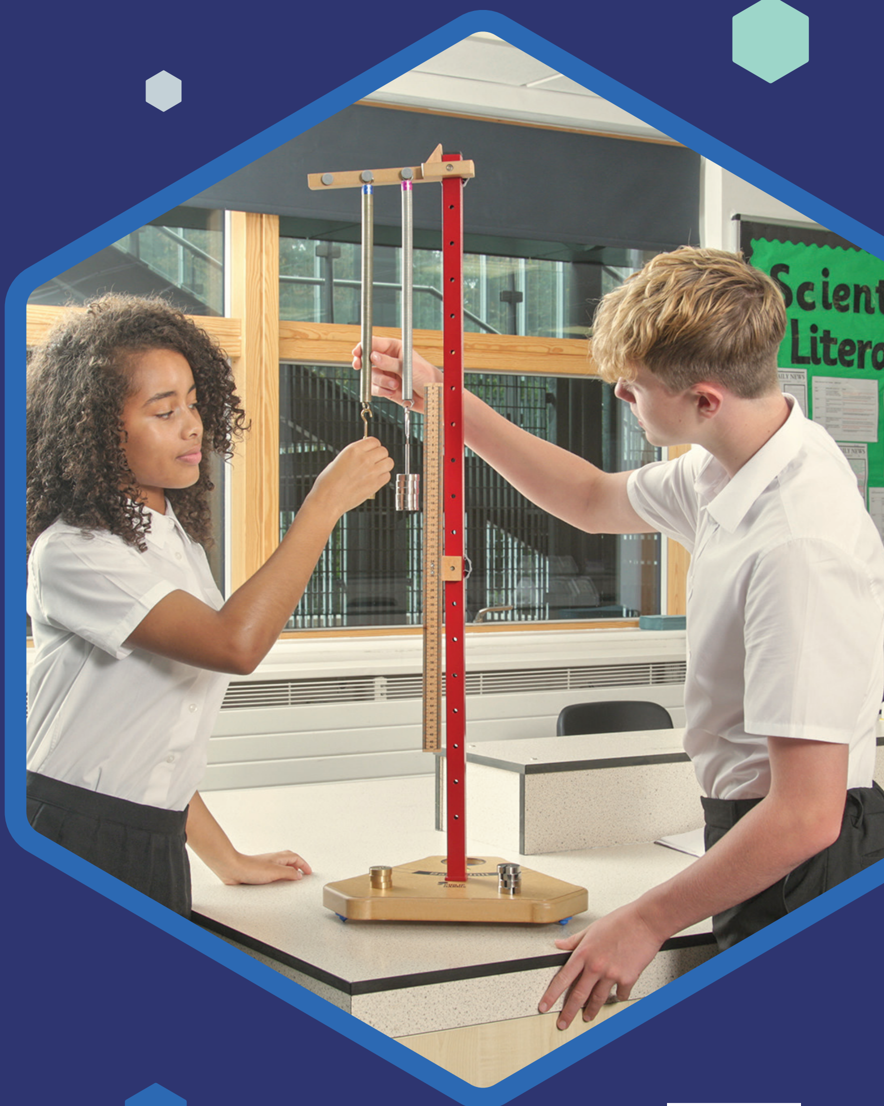

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