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The challenge to educational reforms during a global emergency: the case of progressive science education

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Abstract:

This article argues that what are most at risk in schooling during a global pandemic, or other similar broad challenges to normal functioning, are those elements that might be considered the less traditional, and so the most progressive. After setting out some general background common to the challenge faced by schools and school teachers generally, this argument is exemplified through the case of school science education. Two particular aspects are considered, one related to pedagogy (responding to learners' alternative conceptions or 'misconceptions'), and one related to curriculum (teaching about the nature of science). These are considered 'progressive' features in the sense that they have widely been championed as a way of improving and reforming science education across a wide range of national contexts, but can be understood to have faced resistance both in the sense of being opposed by 'reactionary' stakeholders and in terms of the level of support for teacher adoption. It is agued that at a time when the education system is placed under extreme stress such progressive elements are at particular risk as they may be viewed by teachers and administrators as 'extras' rather than 'core' features of practice, and/or as reflecting more 'difficult' educational objectives that may need to be de-prioritised (and so neglected) for the time being. In that sense they are fragile aspects of practice, that lack the resilience of more established, and so robust, features. It is concluded that where progressive elements are especially valued they need to become sufficiently embedded in custom and practice to no longer be viewed as luxuries, but rather to be recognised as core elements of good teaching, in order to be protected and maintained during a period of emergency.

Keywords:

constructivism - dialogic teaching - online learning - progressive science education - reform resilience - teaching nature of science

Introduction

The COVID-19 context

2020 was a year 'out of the ordinary'. The new coronavirus identified in China in 2019, COVID-19, quickly became recognised as a global issue early in 2020: as a pandemic affecting all parts of the world. Societies that considered themselves advanced technologically, economically, even ideologically, found that 'business as normal' was interrupted. Health services faced being overwhelmed. In various parts of the world many people were asked, told, or indeed ordered, to stay at home, and only to leave the house for essential activities, for periods of weeks or even months. Often the guidelines, rules or regulations were changed frequently and at short notice as authorities (a) came to terms with the nature of the illness, potentially effective treatments, and the rate and mode of transmission of the virus (and its variants), and (b) sought to balance the warnings from epidemiologists against considerations of (i) the (economic, social, and well-being) costs of disrupting normal economic and social activity; (ii) the undesirability of impinging upon the usual rights of individual citizens (e.g., free movement, freedom of association); and, indeed, (iii) the need to lever public co-operation with the restrictions being imposed.

Education systems were, at times, faced with high absentee rates due to illness, self-isolation of those thought to have been exposed to infection, shielding of those most at risk, and individual decisions to keep students at home. Then, there were periods with partial or complete closure of school and college buildings. Teachers might be expected to both work directly with the children of those considered to be doing essential work who needed to be kept economically active, as well as provide education for the majority being asked to stay at home. In principle at least, in many contexts, education moved 'on-line' for extended periods of time. Teachers would teach, and students would learn, via the Internet.

That simple description belies myriad complications. Two obvious ones are connectivity and hardware. Effective distance learning through the Internet requires a reliable connection with sufficient bandwidth. It also requires enabled devices - a computer of some kind with the requisite applications. In some communities, in some parts of certain countries, these might largely be taken for granted. Yet access is an equity issue when some learners do not have broadband connections or regular access to a connected device, or a safe, comfortable and quiet space to go online. In other parts of the world, good connectivity and personal access to a suitable computer may be the exception - or indeed lacking across a whole community.

Teaching relies on a social contract between teacher and learners

Even in an ideal context, where a teacher and all her class are well connected, there are significant challenges to school teaching, both in primary (elementary) and secondary (high school) contexts. As most people today are encultured into societies with school systems it is easy to overlook how schooling is far from a natural system of education. That is, humans evolved to be capable learners within certain social contexts - usually small groups whose members have graduated and progressing levels of expertise (Lave & Wenger, 1991). We still find something like this in the post-graduate education of scientists (Kuhn, 1970). The noice joins a specialist laboratory or research group as a new research student alongside other group members who are already further along in their programme of study (established research students, post-docs who have graduated beyond that stage; and university lecturers and professors with considerable experience and expertise).

Such a context allows prolonged engagement with specific areas of learning, a high level of commitment to, and ownership of, a personal project, individualised learning paced for the particular learner, and opportunities to learn specific skills, techniques or ideas on a 'just-in-time' basis. By contrast, school (and much undergraduate) education is based on a model of one expert teaching a large number of novices in short blocks of scheduled time. Of course, this is more efficient for mass education in logistic and economic terms (and the usually tacit child-minding function of schooling has become explicit in public discourse during the pandemic), but means that students are often not learning something they are especially interested in, and to a large degree all those in a specific class have to progress through the curriculum together despite individual differences. In many ways, the successes of teachers in so often managing, motivating, and supporting student learning in school classrooms and lectures halls should be seen as an incredible achievement - relying on the strong interpersonal skills of teachers as much as their knowledge of the curriculum. The ability of a teacher to engage a diverse group of learners in a topic in which most have little *intrinsic* interest (as is often the case in school teaching) is something that can too easily be taken for granted - but, as new teachers often discover, is far from automatic.

What keeps students in the classroom, and hopefully paying attention, is certainly *sometimes* intrinsic interest in lessons, and may *sometimes*, in part, be a threat of some form of formal chastisement, but, often, is largely a kind of social contract between learner and teacher. Teachers who are judged to be respectful to, and interested in, their students, and seem to care about them as individual people, and who clearly make an effort to give interesting and informed lessons, are *usually* rewarded with the *default* of *most* students not being disruptive, and, further, acquiescing in reasonable requests to undertake specific activities, and to moderate the natural human tendency to chatter at will.

Once the 'social contract' of the classroom is negotiated (whether explicitly, or tacitly); once a good working relationship is established, both 'sides' will be able to earn some credit to be forgiven some occasional lapses without this being seen as a threat to the established norms. A student will be forgiven the uncharacteristic slip - a misjudged joke, a yawn, a few minutes daydreaming - just as the students in a class will understand and forgive the usually fair, reasonable, and conscientious, teacher who is very occasionally ill-tempered or does not seem to have prepared well for a particular lesson, or who tries something new that does not seem to be working. A teacher who, obviously, usually makes an effort to engage students in sequences of interactive activities can occasionally - on account perhaps, for example, of a headache or sore throat - persuade students to spend a lesson in quiet reading and note-taking that would otherwise be objected to as 'boring'. There is there an (at least implicit) agreement: we may not get as much learning done today as usual, but we will have an orderly and peaceful classroom where I will tolerate some quiet chatter and you will at least engage to some extent with the task I have set.

Students do not generally put down their work and walk out of the classroom mid-lesson, or ignore the set task and engage in some unrelated activity for extended periods, even when they might be tempted, as this would be an *overt* contravention of the social contract and the teacher-student relationship on which it is founded. This restraint is however in part maintained by the nature of the setting. The teacher can normally see the whole class. Moreover, when the teacher is busily engaged with an individual or group of students the classroom has something of the nature of the panopticon (Foucault, 1991/1977) in that the activity of the students is visible to their peers, and students will often join in the processes of monitoring and regulating the classroom (e.g., through announcements along the lines of "Miss, Jenny is looking at her phone", "Sir, Tommy has put his books away and there's still ten minutes left").

Changing the mode of teaching

Working 'on line' is clearly a very different proposition. When students are highly motivated to learn and make the best of the activity - adult students for example who have enrolled themselves on professional development courses or postgraduate programmes - the teacher does not need to be so concerned about maintaining engagement. But, in a school teaching context, it is not as easy to monitor a class of 30 adolescents each working on a device at distance, as it is when they are in the room with the teacher, when eye-contact can be made with any student in a moment. It is not so easy to notice someone who has absented themselves from the lesson, or to see what the face apparently looking into the webcam is actually paying attention to on the screen. A child who leaves the computer and exits the room may do so *covertly*, without obviously breaking the usual contract. Leaving all microphones on at once is a recipe for noisy distractions - but muting microphones looses spontaneity of the usual classroom dialogue as well as a key mode for monitoring student activity.

Moreover, teaching on-line is unlikely to mean just doing the same lesson via computer. There are many activities that do not unproblematically transfer to home based learning. Practical work in the sciences is an obvious case. Artefacts and models that may usually be manipulated cannot be engaged with as directly. Key resources usually available in the classroom may not be available on line.

That said, there are likely relevant alternative resources on line that could be accessed. After all, the Internet gives access to the World Wide Web offering a virtually unlimited range of resources. For most courses, it would be possible to find excellent, suitable resources on line. When planning an on-line course *in advance* the identification and evaluation of resources would be a key task. Yet, that is not possible when suddenly being told that a course normally held in school or college is *now* to be interrupted and continued virtually. The sheer volume of Internet-accessible resources is matched by a diverse range in quality, and indeed a considerable level of misinformation. Curation of reliable, curriculum-matched, and correctly-pitched resources is a critical task in planning teaching. Regardless, then, of any question of whether some material can, *in principle*, be taught on line as well as in person; there is the issue of the time commitment for *advanced* planing of a coherent, well organised, and well resourced course (Taber, 2018a): something that clearly can not happen when schools are summarily closed, and the mode of teaching switches, with virtually no warning, overnight. This challenge of switching modes for whole classes is exacerbated when working with classes that are split between those attending the school (and probably reorganised into novel collectives) and their classmates requiring teaching at distance.

Teachers develop expertise through specific teaching experiences

Teaching is honed over time. A strong understanding of subject matter is clearly important for effective teaching - as is a good appreciation of general principles of pedagogy, and a knowledge of the specific curriculum requirements set out as target learning for a particular course. Teachers not only need the pedagogic content knowledge (PCK) relating to common learning difficulties and teaching approaches in a topic (Kind, 2009) but arguably also develop a specialised form of their own subject knowledge through experience of teaching it to learners at a particular level.

So, for example, we might consider that academic chemists who undertake research in different areas (say, synthetic routes of natural products, as opposed to light-catalysed reactions or electrochemistry) each develop a particular form of subject knowledge which although it may encompass the whole discipline, has particular depth, detail, nuance, and density of associations, focused on the area of specialist study. By comparison, the school chemistry teacher may seem a generalist, but *actually* also develops specialised subject knowledge which is especially rich *in relation to* how the subject matter is processed in preparing and carrying out teaching. That is, in relating subject knowledge to PCK (e.g., common misconceptions, useful metaphors and analogies, suitable simplified teaching models), the teacher also develops a particularly rich subject knowledge which is in its own way a form of specialism (Taber, 2020).

Knowing the subject and knowing how to teach are starting points, but do not automatically lead to effective teaching. The teacher gets feedback through the practice of teaching: refining ideas about what works well, why a supposedly sensible sequence needs to be modified, how much longer a particular activity actually needs with a certain type of class, what level of understanding it is reasonable to expect after first introducing a new concept, etcetera. Substantially changing the way in which teaching takes place acts as a kind of reset.

Just as when a new curriculum is introduced, or an innovative teaching approach adopted, a shift to a new mode of teaching changes the process: perhaps, a concept that had previously been readily explained suddenly becomes more opaque to learners, perhaps an activity that normally takes 20 minutes now only needs 15, perhaps paired or small group work that usually works well at some point would be better be substituted by something different. Yet these are *empirical questions* that can only be addressed, and indeed may only arise, as teaching proceeds. This is something often ignored in experimental studies of teaching innovations, where it is common to see well-established practice used as a comparison condition against some novel pedagogy, curriculum, or teaching resource that study participants are using in their teaching for the first time (Taber, 2019).

The global pandemic of 2020-1, then, meant that teachers not only shared in the common complications of the pandemic (risks to health, restrictions on travel and socialising, worries about at-risk relatives and friends), but also faced specific additional challenges in their professional work: including sudden shifts to less familiar modes of working, and the need to reorganise their lessons and courses without the time for advanced planning that is normally expected when making any substantive change to professional practice. In some cases, teachers may have been expected to simultaneously continue with planned teaching to reduced classes, whilst also trying to offer the same curriculum to other students now working away from school. No matter how well intentioned, committed and hard-working teachers may be, the COVID-19 pandemic introduced challenges which inevitably impacted upon the quality of teaching and learning. Inevitably, when faced with such increased demands and new challenges, teachers will need to prioritise, and to adopt coping strategies. I have been told by one colleague that a much heard phrase in conversations between teachers was "it is what it is". Inevitably, some things that were previously recognised as important, desirable, and/or good practice, will be casualties of the emergency.

This article explores what seems a reasonable *conjecture*: that in an emergency situation (such as being suddenly required to 'deliver' the curriculum in novel and unfamiliar ways), what will be sacrificed in order to 'make do' will be those things seen as desirable *but* difficult. These are likely to comprise those elements of teaching considered 'reform' practices. What is understood here as 'reform' is what is still widely seen as novel and challenging and so often perceived as 'difficult', and perhaps even as luxury. What is *necessary* (for teachers) is to teach the curriculum. What is by contrast seen as *desirable* is to incorporate those aspects of good practice which are still yet to be fully consolidated into 'custom and practice' and are still conceptualised as reforms. Another term that might be used instead of 'reform' might be 'progressive'. It is suggested that those features of a teacher's work which are still perceived as reforms or progressive are most likely to be less robust, and so less resilient, in response to stressors. The scenario offered in this essay may be considered to present hypotheses that can subsequently be tested in research on the impact of the pandemic on education in various contexts.

Progressive science education

The term 'progressive' implies going beyond what is currently taken as standard fare or the norm. Formal education - such as schooling - is a social phenomenon depending upon cultural institutions. That is, what is introduced as a reform and seen as *progressive* in one cultural (e.g., national or institutional) context may be viewed as *unexceptional*, or conversely *radical*, elsewhere. Indeed, in terms of educational reform it is likely that there is a common pattern of a proposal being initially seen as radical (as 'left-field') before it is later adopted as a reform and considered progressive, and then later still becomes custom and practice (see figure 1).

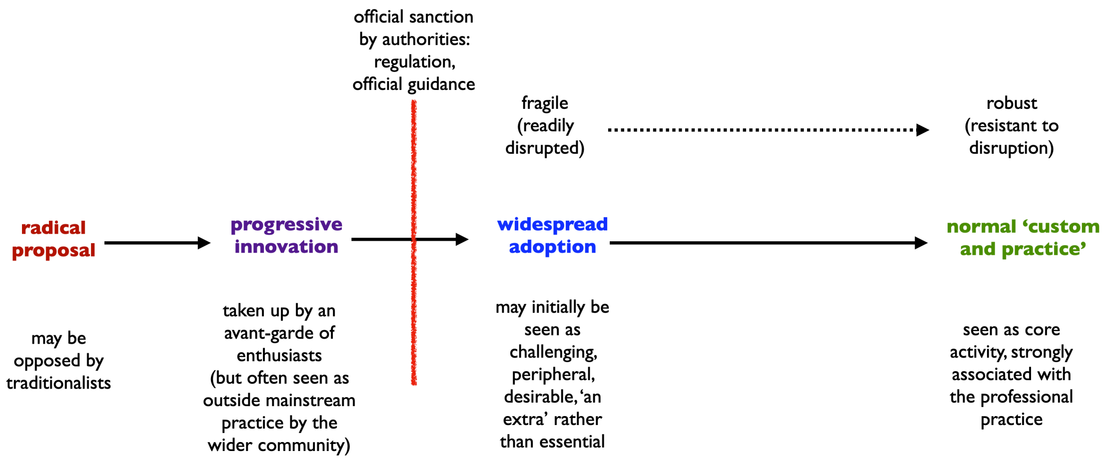

Figure 1: Initially fragile features of practice become more robust over time

Educational norms shift

As an example, consider how curriculum has shifted over time, and still varies somewhat in different parts of the world. The medieval university curriculum was at one time dominated by the common study of the trivium (grammar, logic, rhetoric) and then the quadrivium (arithmetic, astronomy, music, and geometry) - whereas today the norm is that undergraduates specialise, and from a much wider range of subjects such as chemistry, art history, sociology, civil engineering and so forth. Moreover, whether it is appropriate to have university degree courses in subjects such as media studies, sports science or, indeed, education, has at various times been the matter of debate (and subjects that are accepted in some universities or countries would not be in others).

In the English system an undergraduate would often focus primarily on one discipline with a modest complement of subsidiary subjects (usually from fairly cognate disciplines). However, U.S. undergraduate courses often have a 'liberal studies' aspect such that a student may be required to study some science even if they are specialising in the humanities (Bourke et al., 2009), and Chinese undergraduates are expected to study some aspects of a common curriculum such as mathematics, English, and state ideology (Zhang, 2012).

At one time post-elementary school education in some countries took place in institutions known as 'grammar schools' - a term which was descriptive of their main focus, Latin grammar. No doubt the addition of Greek would have initially been seen as a radical reform. The introduction of subjects such as the natural sciences into mainstream schools was also initially a progressive notion - which has become so taken for granted that any suggestion today that schools should not teach science would seem bizarre (and, now indeed, radical). Again, such a change was not uniform across the globe: for example, when the teaching of natural science was still seen as a novelty in the English school system, an official government report (Schools Inquiry Commission, 1868) not only pointed to where the innovation was being adopted around the country, but also to how the (more progressive, in this sense) French, German, and Swiss, school systems were already embedding this curriculum reform.

Fragile features of school science education

What is considered as progressive not only changes over time, but is also relative to local norms. In this article I am going to identify and discuss two aspects of science education which I will conjecture can be widely considered as progressive. That is, these two features represent aspects of science education which (a) have been much discussed and championed in the literature, (b) have been incorporated into educational reforms in a range of national contexts (although are not yet globally fully adopted), but (c) are still recent or current enough reforms in many contexts as to not yet be sufficiently consolidated into custom and practice to be robust enough to avoid disruption at a time of substantial challenges to the system. They might be considered as progressive features that are still 'fragile' (see Figure 1) - those that lack 'resilience'.

Space does not here allow an account of how these features have been adopted to various degrees in different contexts. Discussion of how these progressive elements have been *nominally* formally adopted in the English curriculum context, yet in a way too superficial to support teachers in deep engagement, can be found in other articles (Taber, 2010, 2018b). One of these fragile progressive features relates primarily to curriculum, and the other to pedagogy. I will describe each of these features, with some background on the arguments for their adoption in school science, as well as discuss why they might be considered fragile and so vulnerable at a time when the school system is highly stressed through an emergency such as the global COVID-19 pandemic.

Progressive curriculum: teaching about the nature of science

The school science curriculum is organised and understood in somewhat different ways in different parts of the world (Taber & Vong, 2020). There have been various arguments about whether or when (i.e., for which age groups) science could be taught as a single subject ('general', 'coordinated' or 'integrated',) rather than as discrete school subjects representing discrete disciplines (Jenkins, 2007). In the United States it is quite common for earth science to be seen as a major division of school science alongside the biology, chemistry and physics that have long been seen the main school science subjects in some other countries (Orion et al., 1999). Astronomy has been taught in some schools. Psychology has sometimes been accepted as a school science subject, and in some countries geography is seen as a science (although of course we should be careful not to assume that labels such as 'geography' are understood to cover the same *range* of content everywhere).

At one time in English schools it was possible to take examination courses in subjects such as rural studies or engineering sciences. In some national contexts mathematics has been seen as a science subject. In many parts of the world there has been a focus on 'STEM' (science-technology-engineering-mathematics) or related notions (Chesky & Wolfmeyer, 2015), such as 'STEAM' incorporating agriculture (Sumida, 2018), as a curriculum area - whether seen as a higher-level subsuming category (within which science, or the sciences, will still be discretely taught) or a better focus for the school subject itself.

In part, the discussion behind the merits of making these different choices has been about the scope of natural science to be included in the school curriculum; but, clearly, another issue when considering (i) whether to combine or separate sciences, or (ii) whether to form a unitary school subject of science with mathematics and technology, concerns what is common across the sciences. Whereas decisions about how much space science or earth science to include in school science are questions about disciplinary science content (i.e., the *products* of scientific activity), there has increasingly been a complementary focus on *scientific processes*. Put simply, this reflects the question of to what extent should school science education be about learning about some of the 'products' of professional science (the theories, the models, the laws, the typologies, the catalogues of 'facts', and so forth), and to what extent should it be about learning about science *qua* science (e.g., as a set of practices within a professional community).

The complementary aims of education

There are various potential aims of school education which include facilitating progression to further education and employment; the development of generic areas of skill (such as critical thinking, problem-solving, creativity); the introduction to the key cultural domains valued by the society; supporting personal growth (cognitive, conceptual, ethical, physical, spiritual…) of young people into happy and healthy adult individuals; and the production of citizens prepared to engage in the civil society (for example as voters or as responsible and informed consumers).

Curriculum choices should sensibly be informed by how these competing aims are prioritised. A decision to pack the science curriculum with as much content as possible probably only makes good sense in terms of a focus on progression to higher education; *and then*, only for those competing for admission to tertiary level courses; *and even then*, only as long as Universities prescribe admissions requirements based on such a breadth of coverage in the curriculum. An in–depth focus on fewer topics might better support intellectual development by allowing greater engagement and a more sophisticated treatment of topics; a focus on the needs for informed citizens might also suggest a greater focus on a more select groups of topics chosen in relation to societal priorities (e.g., healthy living, the environment, the climate, sustainability).

The NOS turn in science education

It has been widely suggested that the school science curriculum should put more focus on what is often known as the nature of science or NOS (Allchin, 2013; Clough & Olson, 2008; Driver et al., 1996). Young people need to understand what science is, and 'how it works' (Toplis, 2011), as this will be important for both the minority who become scientists as well as the rest who will engage with science as non-professionals who will vote, spend, recycle (or not), choose (e.g., medical treatments), and so forth in situations impacted by science.

The nature of science is contested, and professional accounts are subtle and nuanced, but there is a general consensus on key features that should be represented in school science (Lederman & Lederman, 2014). Just as many science topics that are traditionally taught have to be modelled and simplified in the curriculum to be suitable for presentation to school age learners, curricular models of NOS can be developed (Taber, 2008). There is an extensive literature about these issues, but here I offer one illustration.

The key topic of scientific knowledge

One of the biggest challenges for school science teachers is to offer learners a sense of the nature of scientific knowledge. Scientific knowledge is largely conceptual and theoretical - and a key principle is that strictly it is always provisional. In principle, all scientific findings are open to being challenged in the future in the light of new evidence or new ways of thinking about the existing evidence (the Copernican revolution and Einstein's ideas about relativity were new ways of thinking that did not depend on any new data). Yet, we also want learners to appreciate that science is the most reliable means we have of learning about the natural world, and that scientific knowledge is often a very good guide to action in the world. Newton's laws of motion are rightly lauded as having been a major scientific achievement, and are still taught in schools today. For two Centuries they were widely considered definitive knowledge, although we now know they are strictly false (yet under most circumstances work well enough - e.g., in the calculations that allowed people to get to the moon and back safely).

The nature of scientific knowledge is clearly not an easy topic to teach to school children - it is an aspect of philosophy of science. Yet, if we want young people to understand, as one critical example, the nature of climate science and public policy debate about climate change, then this becomes essential. Science offers a strong consensus on the effects of anthropogenic inputs into the climate, *albeit* a small minority of scientists do not accept that general consensus. The best scientific models offer predictions, yet these are necessarily imprecise and probabilistic, and are regularly revised, suggesting earlier versions were not quite right. It is easy for the lay person to listen to the scientific climate heretics, and to look at the imprecision and updating of predictions, and conclude science does not *yet* 'know' and therefore we might best defer action until the scientific knowledge is definitive. So, it is important for children to understand that provisional, theoretical, knowledge is all we will ever have, and waiting till we really know (i.e., for absolutely certain) before acting on the science is illogical and dangerous.

Learners should not believe scientific knowledge

It also useful for teachers to bear in mind that if scientific knowledge is always conjectural and provisional, then it is not their role to ask learners to believe in it. Many people will have learnt scientific ideas at school that have since been demoted from the scientific canon. Science offers us useful ways to understand the world, but not an absolute, eternal account. So teachers should ask learners *to understand* why an idea is useful and why scientists came to suggest it (i.e., in terms of evidence and arguments) - but not to *believe* in the idea (Taber, 2017). As an example, it may be appropriate to teach that general relativity is the best currently available approach to understanding gravity, but it is not in the spirit of science to ask students to believe in the theory of general relativity. Similarly, it may be sensible to teach the 'lock-and-key' model of enzymes and substrates as a useful way to think about enzymatic specificity, but it does not make sense to ask students to believe the model. Asking learners to believe in such things would reflect a category error as theories and models are not the kind of entities where belief-disbelief strictly applies, unlike factual claims about what is the case which can be considered to have truth values (e.g., the claim 'Slovenia is a monarchy' would be false).

Science education should have a strong focus on science as producing models and theories which are often useful in limited ranges of application (e.g., the ideal gas equation), and have to be developed further before they can be applied more precisely or more widely. This would avoid a student, for example, learning a shell model of the atom as some kind of absolute truth, and then finding they are being asked to move beyond this and learn a different account (also just a model, and not an absolute truth): something that can be experienced as having been taught something 'wrong' which now needs to be 'unlearnt'.

Moreover, teachers in many contexts find they are teaching students who for cultural and religious reasons are committed to 'truths' that are inconsistent with some scientific ideas. The paradigm case here would be rejection of macroevolution by natural selection by those who consider that their faith requires them to believe in the discrete special creations of different types of animal and plant groups (Reiss, 2008). Teachers cannot avoid the contradictions between these two perspectives (without abdicating their responsibility to teach the science, cf. Long, 2011), but there is a big difference between asking learners (a) to *believe in* macroevolution (which logically requires rejecting their faith) and (b) to *understand* the theory and appreciate the grounds on which it was suggested and why it has become the key organising idea in modern biology. The intellectual clash of ideas is just as great, but without asking for a commitment to a scientific theory as if it was a creed. (Just as in other areas of the curriculum the same students might be asked to *understand* the viewpoint and actions of a historical figure or of a fictitious protagonist of a novel without being asked to commit to their beliefs, views, or choices.)

The increased focus on the teaching of NOS may, *inter alia*, include more emphasis on enquiry, including historical case studies to show how scientific advances may be difficult and contested, rather than just the retrospective, whiggish, teaching of what has been called a 'rhetoric of conclusions' (Schwab, 1958, p. 375); and engaging with socio-scientific issues (Sadler, 2011) where science can *inform* social policy, but where decision-making also depends upon consideration of extra-scientific values (e.g., science might quantify the risk of building a nuclear waste storage unit or the cost of setting aside an area to protect at–risk species, but cannot tell society how much risk is acceptable, or what cost is worth paying).

It is widely recognised that there can be a considerable lag between the changing of a formal curriculum in terms of documentation and the full acceptance and enactment of the reforms (Peskova et al., 2019). The degree to which aspects of NOS have been incorporated into curriculum and teaching standards, and have become part of local custom and practice varies internationally. In many places this is still progressive, and not yet a robust, feature of teaching. Indeed, in the English curriculum context, contra international trends, there was a de-emphasis of NOS in the most recent curriculum revision (Brock & Taber, 2019).

It can be considered 'challenging' for many reasons, including (a) teachers' own scientific education is often lacking in NOS; (b) in many countries high quality texts and teaching resources have not yet been developed to support this area of teaching; and (c) teaching approaches may require different pedagogy and teaching skills from those most science teachers have mastered. For example, neutral chairing of a debate about a socio-scientific issue is quite different from teaching an area of established content; and engaging with historical sources requires an interpretive approach open to multiple viewpoints, which is not the way science is usually taught. Teaching NOS is, in many national contexts, 'difficult' from the teacher perspective, and so is a 'fragile' aspect of practice (cf. Figure 1). When under the stresses resulting from a crisis, it seems inevitable that for many teachers there will be a reversion to focusing on teaching specific science topics, and so learning about NOS will suffer. That is, a reasonable hypothesis is that in some educational contexts curriculum revisions to put more emphasis on learning about the nature of science may lack the resilience to be maintained during a period of systemic stress (and so it is likely teaching about NOS was less extensive in these contexts during the year 2000 when education norms were disrupted by the global COVID pandemic).

Progressive pedagogy: taking learners' conceptions into account

The other example I wish to highlight is teaching that takes into account learners' conceptions. The educational psychologist David Ausubel (1968) famously suggested that if he had to reduce the whole of educational psychology to one principle it would be to find out what the learner already knew - and teach accordingly. This resonates in science education where much research has highlighted how students commonly form alternative conceptions ('misconceptions') in science topics (Driver et al., 2013). That is, learners often come to school already having their own proto-concepts about natural phenomena, and teaching is often either resisted due to being inconsistent with, or inadvertently mis-interpreted to fit with, prior understandings (Gilbert et al., 1982). Commonly, teachers have to work reshape learners' initial thinking, to challenge some alternative conceptions, and to find ways to constructively build upon learner intuitions to channel thinking in the desired directions (Driver & Oldham, 1986).

Again, there is a vast literature (Taber, 2009) and it is not possible to do justice to this area of work here. There are various teaching schemes, and particular techniques that have been recommend for teachers. A key feature of the kind of teaching needed, what might be called constructivist teaching, is that it is interactive (Taber, 2018a). It starts with (à la Ausubel) diagnostic assessment to identify the students' current thinking. The teacher then seeks to persuade learners towards the scientific view, not simply by presenting that view but through demonstration, argument, discussion, metaphor, analogy, modelling, and so forth (Hadžibegović & Sliško, 2013; Kress et al., 2001; Lemke, 1990; Mortimer & Scott, 2003). Most importantly, the teacher is constantly using formative assessment to check how teaching is being understood - checking 'where is student thinking now?' The teaching needs to be dialogic (Mercer, 1995) - to have the form of a conversation where the learners' voices are heard. This has often been misunderstood as some kind of relativistic notion that all ideas are equally valued. The teacher *does* value the students' ideas but not because they are as worthy as scientific accounts, but because learning is always interpretive, incremental and so iterative (Taber, 2014), and the students' current thinking is the 'material' available to be worked with to bring about learning and conceptual change.

Again, this kind of approach has been adopted to varying extents in different places. In some parts of the world the basic principles behind this type of science pedagogy have been reflected in teacher education, curriculum reforms, and official teacher guidance for some years. Effective practitioners do present the scientific accounts, but as part of a choreographed practice of eliciting, reflecting, discussing, and challenging, students' ideas, and of giving learners frequent opportunities to reflect on and work with the ideas the teacher is presenting (Mortimer & Scott, 2003). This kind of teaching is, by its nature, conversational. It is like a symphony, shifting between themes (the received account, the different student notions), shifting between different solo instruments and ensemble playing (teacher exposition, class discussion, individual reflection, paired and small group discussion).

Teacher talk is not all one-way: it is rich in questions and invitations for suggestions, to ensure everyone is following, everyone understands, and everyone's ideas are getting a hearing. All ideas (whatever the source) are open to communal critique in terms of logic, evidence, argument structure, and coherence with other ideas we accept. This also models the core scientific value of questioning and testing all contributions on their merits. If this style of teaching becomes too difficult, this not only means a less effective way of teaching science concepts, but the loss of an implicit way of reinforcing a key feature of NOS.

Again, in a time of great stress on schooling and teachers, it is likely that those practitioners who are less experienced at these techniques, where such practice is still 'fragile', will readily slip back to 'teaching by telling'. Moreover, it seems likely here that even those teachers who have mastered such approaches and have made them part of their normal custom and practice (such that they can be considered 'robust' rather than 'fragile'), may be challenged to teach in this way when faced with a class as a set of tiny muted headshots on a computer screen. That is, a reasonable hypothesis is that in some educational contexts pedagogic reforms to better support student construction of knowledge through dialogic teaching may lack the resilience to be maintained during a period of systemic stress (and so it is likely that in these contexts science teaching tended to revert to direct communication of the 'received' account during the year 2000 when education norms were disrupted by the global COVID pandemic).

Perhaps, with the right technology, and time to test out methods of teaching, it will prove just as effective to teach science taking into account learners' ideas via the Internet as it is in the classroom (Taber & Li, 2021). The use of chat rooms and the like can substitute for breaking the class into small groups for face to face discussion (and without groups distracting, or 'borrowing' from, each other). Wikis or shared glossary tools may be used to collect different learners' ideas and suggestions simultaneously, and possibly more effectively, rather than sequentially asking each learner or group in a classroom. Yet, even if that is true in principle, it will not be a straightforward transition, but rather something that will require development and practise, just as any 'reform' does. So, *it may be* that teaching virtually is not in itself the challenge, but rather the sudden shift between classroom and virtual teaching without suitable warning and preparation. It is also *possible*, however, that distance learning (with the technology available today, at least) simply does not lend itself to effective science teaching as well as the classroom.

Conclusion

This article makes an argument that the stresses placed on the school system during the COVID-19 pandemic will inevitably impact on the quality of the teaching and so student learning, and that this will disproportionally affect those aspects of teaching which might be seen as desirable but not essential to 'delivering' the curriculum, and which are felt more 'difficult' and so need to be put aside when seeking to 'make do' and 'get through' in a crisis. Well-established aspects of custom and practice are likely to be robust features of teacher practice, whereas elements associated with 'reform' elements and so still seen as progressive are more 'fragile' and subject to being given a lower priority. An obvious challenge to science teaching in lock-down conditions is laboratory practical work which despite being a robust aspect of science teacher practice in most counties presents major logistical challenges to moving on line.

In this article I have however focused on two other areas where I predict science teaching quality will have suffered, two areas that have over many years been much discussed in the literature, and which have to varying degrees been adopted as aspects of educational reform in many national contexts. One prediction is that teaching about the NOS will have suffered more than teaching science content in those contexts where teachers still find this a more challenging and/or peripheral aspect of their work. The other prediction is that the kind of dialogic teaching at the core of constructivist approaches which take into account learners' ideas, which is seen as critical to effective teaching of science concepts, and which relies upon teachers' interpersonal skills in making science lessons more like conversations than lectures, will prove more difficult on-line. For some science teachers, this will still be seen as a 'desirable' rather than 'necessary' aspect of their work, but even where this approach is well-established and so not as inherently fragile, the on-line mode is likely to encourage a shift back to teaching that is based more on a telling of the canonical account.

Hopefully, in time, there will be studies which explore the extent and nature of changes to teaching during the COVID-19 pandemic, and such research will help education systems become more robust in preparation for future crises that might require similar sudden changes in the organisation of teaching. If the findings of empirical work reflect the predictions made here, then part of that preparatory work should involve considering how one protects progressive elements of educational policy and practice in such circumstances. After all, reforms are made to improve teaching and learning, and so it is important to mitigate the fragility of those elements and seek 'reform resilience' in the face of stresses to the educational system.

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