Challenges for Science Education

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Abstract

Scientific knowledge is the common heritage of humankind. It is the only this treasure of humankind that can provide a possible remedy to conquer inequality and to bring about an acceptable quality of life and a purpose, for a majority of the people of the world. A case should be made for science and science education in the developing world, a case for optimal support for science and education even in the poorest and the least-developed of the countries of the world. Some of the main problems that should be overcome for a sustainable and proper science education are:

- Inadequate teacher compensation and professional development to attract, prepare and retain high-quality teachers,
- Insufficient number of science and technology teachers’ taking active role in the preparation of the programs,
- The insufficient in-service training of the science teacher in the transition state of a new program,
- Compartmentalized subjects taught by teachers isolated within and across departments,
- Students generally lack motivation and have low self confidence in learning,
- Persistent achievement gaps in science and math among many student subgroups,
- demographic changes,
- The huge numbers of the students in the class,
- The informational education orienting students towards only exam achievement,
- The broken link with other lessons,
- Insufficient physical conditions of schools (less laboratory opportunities),
- The intensive curriculum but insufficient time allocation for science education and
- The instruction of lesson in an information level and students in passive position (only listening and writing), teachers in active position (writing on the board and teaching in a classical way),

In this paper, the problems of challenges for science education and solutions to overcome these problems are presented. The lack of epistemological role of science is emphasized and the productive use of history and philosophy of science is proposed in science education.

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1. Introduction

The relevance of science to the future of society is likely to be considerably more far-reaching than its influence on human affairs in the past. Some of the pressing problems of society today are related to the rapid decline in the quality of global environment, depletion of natural resources, increasing poverty, hunger and illiteracy in many countries and regions of the world. Solutions based on science and technology are likely to provide remedial measures to some of these problems, and yet science and technology as we understand today, are not available to a vast human population. It is essentially in the advanced world that science and technology have contributed to individual fulfillment, the well-being of communities, and to the health of nations. A high percentage of the human population does not understand science or its utility, and its potential for economic and social development. There is a tendency to get impressed with certain products of technology that may bring in superficial prosperity, but a proper understanding of technological innovation and of the way science and technology are related to society is important for real progress of all countries, particularly the developing ones. Such an understanding is retarded today by the barriers impending the sharing and the use of scientific and other knowledge necessary to make decisions and choices.

That is that science education attempts to wrestle with three mutually contradictory requirements. On the one hand it wants to demonstrate the tremendous liberatory power that science offers – a combination of the excitement and thrill that comes from the ability to discover new knowledge, and the tremendous insights and understanding of the material world that it provides. Yet its mechanism for achieving this aim is to rely on a dogmatic, authoritarian and extended science education where students must accept what they are told as unequivocal, uncontested and unquestioned. Only when they finally begin practicing as scientists and enter the inner sanctum will the workings of science become more transparent. Moreover, its foundationalist emphasis on basic concepts rather than the grand ideas of science means that any sense of its cultural achievement is simply forgotten.

2. The challenge of strengthening science education

There is widespread concern about the outcomes of science education at school. For example, the representatives of industry say that they need more high-grade scientists, technicians, and engineers if any country is to compete successfully in technology-intensive global markets. Whatever their career intentions, too few young people do much science at school once it ceases to be compulsory. This leads to fewer applications for science degrees and reduces the supply of science graduates. Just as importantly, the number of young people entering non-graduate occupations involving science or technology is reduced, which leads to skills shortages in many sectors.

The Review undertaken by Sir Gareth Roberts in 2002 [1] summarised the scale of this problem. It also identified some of its causes. In particular it noted the lack of women choosing to study science-related subjects, reports by students of their poor experience of science education, the shortage of well-qualified and enthusiastic science teachers, and young people’s poor image of science-related careers. The Roberts Report led to the government’s ten-year ‘Science and Innovation Investment Framework 2004-2014 [11].

Yet while the strategy makes some useful references to teacher supply and curriculum issues, it offers little guidance on how its ambitious aims are to be achieved.

The majority of science education research conducted to date has addressed secondary schooling, although research into primary school science identifies similar issues and is referred to where available.

It is important that ‘science education is needed for citizenship’. It would be designed to develop the curiosity of young people about the natural world around them, and help them acquire a broad appreciation of the important ideas and explanatory frameworks of science and how scientific enquiry works.

The processes and ideas of science are of great importance to everybody in three ways. The first is in their personal lives, for example so that they can validly identify the components of a healthy life-style. The second is in their civic lives, so that they take an informed part in social decisions, for example on future options for electricity
supply. The third is in their economic lives, where they need to be able to respond positively to changes in the science-related aspects of their employment.

If the major purpose of science education is to increase the flow of specialist scientists, technologists and engineers, it could be argued that young people with a special talent in science should be identified as early as possible and provided with a separate, specialised, and highly focused science education. Such people share the general need for a broad science education and should not be cut off from it. In any case, there are no valid and reliable ways in which such young people may be identified. Some who show early promise subsequently fade, whilst the talents of others emerge later on. Young people today show an appetite for a broadly-based education based on themes of proven interest, and developing a range of transferable skills. They would resist any attempt to foreclose their choices.

The best way forward is to provide the highest grade of ‘science education for citizenship’ for all students. If that education is sufficiently challenging and interesting, genuine high achievement will become more widespread and will become apparent through students’ creativity, lateral thinking, and persistence. The young people who demonstrate such achievement will be increasingly motivated to follow science-related careers.

What analysis and evidence are available to help promote high quality science education for all future citizens? There must be a greater recognition of what students bring to their studies and how different teaching methods engage with their learning. The diversity in students’ learning strategies must be met by the use of suitable teaching methods. The curriculum must be closely matched to the purposes of ‘science education for citizenship’. The assessment of what has been learned must be closely matched to the purposes of that curriculum. And, central to all of these aims, the supply, development, and retention of high quality teachers must be actively pursued.

3. The background to a strengthened science education

Students bring the legacy of their cultural backgrounds to their studies. They have all experienced science learning outside the classroom and can form and express their own views. This means that they have their own attitudes towards science education and attention must be paid to them.

There can be substantial discontinuities between what young people experience in their school science lessons and in the rest of their lives. Aikenhead [2] has argued that school science expects young people to cross this border, which is more forbidding for some students than for others. Schreiner [3] has explored the way in which student attitudes towards science can be seen as expressions of their identity, whilst Reiss [4] concluded that school science education can only succeed when students believe that the science they are being taught is of personal worth to themselves.

Unless school science explicitly engages with the enthusiasms and concerns of the many groupings that make up today’s students, it will lose their interest. Accordingly, it needs to grapple with how it can respond positively to the wide diversity of student concerns. It must think how to better address women, those who hold strong religious views, those who have little cultural capital, and those whose current or recent roots lie outside Western societies. All too little is known systematically about these issues.

A conundrum for science educators is that school students are being turned off school science lessons, yet the same students are often engaged by science outside the classroom. Science in science museums, hands-on centres, zoos and botanical gardens is often seen as exciting, challenging and uplifting. Newspapers and magazines offer rich sources of science information including debates about controversial current issues. Multi-channel television and the internet have spawned sources of high-quality and attractively packaged information about science and issues of relevance to young people [5]. We are also living in a golden age of popular science book publishing, with a wealth of high-quality science books for children as well as adults.

Students of school age spend about two-thirds of their waking lives outside formal schooling. Yet science educators tend to ignore the crucial influences that experiences outside school have on students’ beliefs, attitudes and motivation to learn. They often see these influences only as a source of misconceptions.

Out-of-classroom contexts can add to and improve the learning of science in several ways [6]. They can promote the understanding and integration of science concepts. Falk and Dierking [7] have reviewed studies that show that science museum visits can lead to improved understanding of such classic school science concepts as force and motion, an improvement measured by tests of knowledge before and after visits. They are also an opportunity to
engage in science activities that would not be possible in the school laboratory either because of safety considerations or because they are too complex. Examples include launching rockets, performing ecological surveys, observing the night sky, and large scale experiments with combustion. How these activities contribute to students’ knowledge of the processes of science is still not clear. And they can provide access to rare material and to ‘big’ science. Science museums, botanic gardens, zoos and science industries provide opportunities for students to see yesterday’s and today’s science in use. Artifacts and collections, and the stories associated with them, help teach about the ways in which scientific and technological knowledge has been generated and about the social enterprise in which those who engage in this work operate. Here too, the exact contribution to school science is unclear. Such activities also provide opportunities for science activities which are less constrained by school bells and lesson times. Work can be more extensive and there are more opportunities for students to take responsibility for themselves and others, to work in teams and to consider their effects on the environment.

But there is more to using out-of-school settings to enrich formal science education than taking students on a day trip. The resource has to be evaluated by the teacher in advance and the students must be prepared for the activity they are to undertake. The activity must be purposeful and produce a record, and the work must be followed up later in the classroom. Other important issues that must be addressed include health and safety risk assessments in all cases and in many instances, travel arrangements and staffing levels [6]. Although out-of-classroom contexts are valuable for learning in science [8], there is much about them that is under-researched [9,10].

What students bring to the science classroom, whether from their cultural background or from out-of-school experience, is reflected in their inclination to form and express their own opinions. The notion of ‘student voice’ emphasises students as active participants in education. Students’ views exhibit diversity, not least between genders, but have provided some indication of the kinds of subject matter which might increase enthusiasm for school science. Students also express definite views on teaching methods, with a dislike of ‘writing’ and an enthusiasm for practical work, especially where they have some real input into its design and interpretation. Jenkins advises caution in interpreting and generalising across these findings, but argues strongly that students’ views are valid and should be explored more completely.

Research suggests that the main factor determining attitudes towards school science is the quality of the educational experience provided by the teacher [12,17]. Part of the explanation for student attitudes toward school science may be a shortage of well-qualified science teachers capable of providing a positive experience. Moreover, many science teachers are required to teach sciences outside their own specialism. This undermines their confidence, leading them to offer a significantly more closed and less stimulating experience [18]. More insights into the nature of the problem come from a recent extensive focus group study [13].

Science is unique among school subjects in that its curriculum aims to create future scientists rather than the future citizen. This produces a foundation curriculum whose coherence only becomes clear for those who stay the distance, and with it the value and meaning of the subject. Moreover, it is dominated by an assessment system whose predominant demand is low-level cognitive recall. Such a system promotes “performance learning,” which is extrinsically motivated, rather than “mastery learning,” which concentrates on the student, to the detriment of student engagement [19]. Those who drop by the wayside are left with a few disjointed pieces of knowledge whose salience is difficult to comprehend.

4. Learning and teaching science

There is now a significant body of knowledge about teaching and learning science. It has been developed through scholarship and empirical studies conducted in many countries around the world. All teachers know that what is taught by teachers is not the same as what is learnt by pupils. As in all acts of communication, learners have to make sense of what they hear, see and read in terms of what they already know. Teachers can make this easier or more difficult for pupils by the way that messages are put together, and the way that pupils’ questions are elicited and answered [19].

This fundamental insight, that learning involves individuals in actively responding to information and its situation, has been developed into several theoretical perspectives which have been used to inform the planning of science teaching. A recent example involves the design and evaluation of short science teaching sequences in the early years of secondary education [20]. Drawing upon a social constructivist perspective on learning, insights about
the treatment of content and patterns of teacher talk were built into the design of such sequences. Evaluation evidence shows that students’ understanding was significantly better when they followed these teaching sequences than it would have been had they followed their school’s usual teaching programmes.

There is very strong empirical evidence that some of the fundamental concepts on which scientific understanding is built are commonly misunderstood by learners, and that there are patterns in the difficulties that they experience. Several ways of addressing this difficulty have been designed and evaluated, with positive results [20]. Evidence of this kind is useful in identifying key conceptual difficulties that are likely to be experienced by students at specific points in the science curriculum. Usable tools for addressing those difficulties can be developed. The insights that come from the research do not lead to simple prescriptions of ‘what works’ and what science teachers should therefore be made to do. But research can inform science teachers as they plan how to tackle difficult content in a way that their students understand, and can help guide their conversations with pupils during teaching.

Significant work has also been conducted on the ways in which classroom communication, and particularly talk, can be used to support pupils in coming to understand scientific content [22,23,24]. This evidence shows how teachers can use different patterns of talk for different teaching purposes. It can be used while working with individuals, small groups or whole classes, and can help achieve aims such as introducing new ideas or supporting learners to use newly-introduced content for themselves.

For teaching to be effective in promoting learning, it must involve interaction between teachers and students. One-way delivery from a teacher does not work for the vast majority of pupils. Assessment for learning (a developed form of formative assessment) is a key element of this interaction. A comprehensive review of the research literature has shown that there is very clear evidence that formative assessment leads to significant improvements in students’ test scores, i.e. their attainment as measured by summative assessment [25]. In the past, science teachers in particular have been discouraged from adopting this approach to assessment.

These developments have involved four main changes. The first has been in classroom dialogue. If teachers are to communicate effectively with students, they must set up activities and questions that help students to formulate and express their own ideas and then listen to what students say. On the basis of this assessment, teachers must fashion the next steps, challenging students and leading them towards ideas which will be more fruitful. Such two-way interaction can happen several times during a lesson as learning progresses. A crucial aspect of such dialogue-based teaching is to give students a voice, and help them realise that their teacher wants to know what they think, so that they will feel free to express even half-formed or confused ideas.

A second change requires interactive feedback on written work. Teachers have to annotate students’ work with comments designed to guide them in making improvements, and then provide opportunities for them to use this guidance. Students then come to see their work as a step in improving their learning. Existing practices emphasise marks, so that pupils see the exercise merely as a test.

A third change is to involve students in working in small groups to assess each other’s work. The point here is not to trust students with generating marks, but to help them help each other so that they are better able to understand the aims of their work and the criteria by which its quality may be judged. Self-assessment is essential if students are to carry on being effective learners in their adult lives.

The fourth change makes use of the formal tests that teachers regularly apply to add extra value to learning. Students may learn from trying to design test questions or from marking test papers in groups so that they can be more objective and realistic in appraising their own performance and in understanding how tests are marked. Working in this way has led students to become more active participants in their learning and to become more motivated to take it seriously.

The implementation of ‘assessment for learning’ has used particularly careful strategy in Scotland. It started with the selection of about 10 schools distributed across the country to carry out a pilot programme, on the basis of a project at King’s College London and with the help of staff from King’s. At the close of the two-year project, a group from another university department conducted an independent evaluation. As this revealed very positive outcomes, a large programme of implementation across all local government districts in Scotland was then mounted. Details can be found on the web-site of Learning and Teaching Scotland [29].
5. Curriculum content and structure

The science curriculum at any level is a statement about the elements of science we choose to teach, selected from a much larger set of possibilities. These choices, for example about the purpose of education, about what is of most value to individuals and to society, and about the balance between intrinsic and instrumental reasons for learning, all embody values. Empirical evidence may inform these choices, but it cannot determine them. Important insights, for example into the nature of scientific knowledge and its implications for learning, have come from scholarship and analysis. Research on the curriculum should include more such work.

Science educators have realised that major trends in 20th century scholarship on science itself, in particular the work of Popper and Kuhn, are important for science education. But much science teaching seems not to have absorbed this lesson. Some writing on science education has acknowledged that there is a tension between inducing students into a structure of agreed and essentially impersonal knowledge and the personal and social values associated with education and schooling. But this insight has been sporadic and has not influenced teaching significantly.

Practical work is a distinctive feature of science education. External stakeholders often regard it as critical to improved student attitudes to science and to the uptake of more advanced science courses. Research evidence consistently shows that students like practical activity in class, often contrasting it with ‘writing,’ which is unpopular. There is, however, less evidence of the effectiveness of small-group practical work, as currently used, in promoting learning. One factor may be the very wide – but often unrecognised – variation in intended learning outcomes and in the cognitive demands of different practical tasks [32].

The growing international interest in scientific literacy as a curriculum aim has increased recognition of the centrally important role of text. Norris and Phillips [33] argue that science depends on written forms of communication, so that text is a component of scientific practice just as empirical enquiry is, and that the ability to analyse and present an argument based on data is an important, though currently under-emphasised, goal of the science curriculum. The same can be said of mathematics, although there has been little research work specifically linking science and mathematics in recent years.

6. Summative assessment

At intervals during, and especially at the end of, a science curriculum, summative assessment takes place in order to evaluate what has been learnt and to provide guidance on future choices.

Summative assessment has a strong influence on the curriculum and on classroom teaching and learning. Students experience summative assessment conducted by teachers for internal school purposes, and in external tests, such as National Curriculum tests and Certificate examinations. These external assessments have much greater impact than internal ones because of the high stakes attached to the results and because of their influence on teachers’ own assessments. There is ample evidence that internal assessment tends to mimic external summative assessment.

Research into current summative assessments has exposed many serious problems [14,26]. They include the excessive burden of assessment procedures and their failure to assess the full range of skills and competencies that should be the goals of science education. This applies not just to students aged 14-19 but at all levels. Current assessment methods narrow students’ learning experiences, in sharp contrast to the broad view of learning goals endorsed in many government documents.

The preference for tests for summative assessment is underpinned by the common assumption that they provide reliable data. However, there is evidence [25,34] that around 30 per cent of students are given incorrect grades or levels by external tests and examinations. These incorrect grades may lead to wrong decisions that affect student progress within and beyond school. Furthermore, the internal tests that teachers devise for practice for the external tests, or to give end of year grades, are frequently of low quality and dubious reliability. And the impact of frequent testing extends beyond the consequences of inaccurate results. For many students it reduces the motivation for learning [35]. The self-esteem of low achieving students is particularly affected, reducing their willingness to put effort into their learning and increasing the gap between higher and lower achieving students.
An additional serious problem with external summative assessment results from its use as important data for evaluation of the performance of teachers and schools. The resulting pressure drives teachers to an over-use of transmission teaching and highly structured activities, in contrast with what is needed for students to enjoy and be motivated to learn science.

7. The supply, development and retention of high quality science teachers

The teacher is the single most important source of variation in the quality of learning [38]. The supply, development, and retention of good science teachers is therefore of paramount importance.

Research on teacher supply has tended to focus on how to attract potential applicants, and thus on their intentions and judgments. Undergraduates have been the main target, perhaps because potential mature entrants are more difficult to reach [36, 37, 39, 40]. Studies show that the proportion of undergraduates willing to consider teaching seriously has broadly declined over the last decade. Despite this decline, potential teachers’ judgments on the character of the job are comparatively stable. Students are often central to the attraction of becoming a teacher. The possibility of ‘making a difference’, of enthusing students and of working with people, rather than with money or things, are important motivations to teach. Undergraduates often cite the influence of their own teachers on them as students. This shows that there is a large pool of goodwill available. But potential teachers are often concerned about their ability to control classes, and that they will be unsupported in doing so.

Teacher training targets in the sciences have been missed regularly, but since figures are not differentiated across the disciplines, and published figures on vacancies are somewhat uninformative, the impact is difficult to trace [30, 31]. The story on supply clearly varies between schools, regions and disciplines. Schools in challenging circumstances often have greater difficulty in recruiting and retaining specialist teachers [28]. The impact of this differentiation on teaching quality is likely to be negative. Polarisation is particularly visible in physics, the major ‘shortage’ subject, but extends more broadly. While 44 per cent of specialists in science departments have qualifications in biology and 25 per cent in chemistry, only 19 per cent have qualifications in physics [27] while the remainder are generalists. It is clear that physics is increasingly taught by non-specialists across the system [21]. Moreover, the level of specialist qualification of the teacher has been found to be the second most effective predictor of pupil performance in physics, after pupil characteristics [21]. This shortage is self-feeding. A small pool of physics undergraduates means fewer and less well-qualified teachers, which leads to lower-attaining students and reduced recruitment to higher education. Across science as a whole the class of degree obtained by PGCE students is somewhat skewed to the lower end [41] although the educational impact of this effect is unknown. There is more to teacher quality than academic qualifications, and Ofsted data presents a positive picture about trainees [16].

Teachers of science usually start their career with good subject knowledge in one or more areas of the school science curriculum. A first stage in professional development is to help trainee teachers translate this knowledge into good ‘pedagogical content knowledge’ (PCK) – the best ways of teaching specific science content and concepts to particular groups of students.

8. Conclusions

We have identified ways in which science education could be strengthened in the light of existing research. We have also identified some avenues for additional research that must be explored if the process of reform is to be progressive. Our conclusions are that:

- The provision of a high quality ‘science education for citizenship’ for all students should continue to be energetically addressed. Its establishment would, we hope, help more students to see the intrinsic worth of a career in science-related fields.
- Every incentive should be given to science graduates to become school teachers. In particular, we suggest that those who remain as full-time science teachers for four or more years should have their student debt written off.
- Science graduates need a systematic and formal introduction to the complexities of teaching science in order to provide a basis for their actions and reflections. The time allocation within the PGCE course for such activities is in
practice limited to seven weeks and for school-based trainees even less. The balance of time-use in initial teacher
training should be reconsidered.

• A national structured programme of continuing professional development should be provided as an entitlement
for all science teachers in post. The successful completion of stages in this programme should be recognised by
incentives such as salary increments and teaching-related sabbatical leave.
• Increased delegation of significant curriculum decision-taking to schools would enable able teachers to see
their profession as an enterprise in which they can exercise their creativity.
• Systematic scholarship is needed into the relationship between the purposes of the science curriculum and the
content of that curriculum.
• Efforts are needed to forge links between science and other subjects, especially English and mathematics.
• Research is needed to establish clear links between curriculum goals and the assessment methods used.
• A range of valid and reliable items that can be used in both the formative and the summative assessment of the
whole range of knowledge and skills that the science student encounters should be developed.
• More research, development, and teacher education are needed on how to increase students’ engagement in
science education. Priorities include classroom organisation, a changed approach to written work, and an increased
focus on the on-task talk that is part of the core of learning science. There should be a strong emphasis on ‘assessment for learning’.
• Systematic efforts must be made to increase the use of out-of-school activity in the learning of science. In
addition, we must know more about the value of different contexts and types of experience. Administrative changes
should facilitate this increased use.
• Much more must be found out about how the gender and cultural backgrounds of students interact with their
learning of science in school. Unless these can be brought into harmony, it is very likely that science that will
continue to be rejected, by many with disadvantages for students and for the UK economy.
• Strategies for linking research, policy formation, classroom practice, and teacher education must be developed.
We believe on the basis of the evidence that if these conclusions are implemented, the quality of science
education for all students will improve substantially.

How can the research and development that we recommend be brought about? There are six types of research,
which in order of impact from the immediate to the long term are:

• Action research, intended to achieve improvement in a particular context of science education and to provide
insights into possible improvements in related areas
• Research into the consequences of existing policies or practices
• Research intended to identify practices that help achieve particular educational goals
• Research to inform policy or practice in a specific aspect of science education
• Research undertaken from particular psychological or sociological perspectives
• ‘Blue skies’ research aimed at generating new knowledge whose impact on practice is uncertain, diffuse, or
long-term [15].

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