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Science Education for the Twenty First Century[*]

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This paper argues that the dominant form of science education that is common across the world rests on a set of values that have no merit. Moreover, such practice has a negative impact on students' attitudes to science. It makes the case that the primary goal of any science education should be to develop scientific literacy and explores what that might consist of and why such an education is necessary in contemporary society. It concludes by examining some of the challenges that such a change might require.

Keywords: Science Education, Aims and Purposes, Educational Norms, Fallacies

INTRODUCTION

Any talk of this nature obviously holds out a promise of a vision of a science education for the future – one that meets the needs and goals of contemporary society. Knowing where you want to go is, I would argue, dependent not only on a vision of where you are now, but how you got there in the first place – that is what are the values and norms embedded in current practice. It is, after all, well worth remembering the Santayana's cautionary remark that 'those who forget the lessons of history are condemned to repeat the mistakes of the past'.

As currently practised, science education rests on a set of arcane cultural norms. These are 'values that emanate from practice and become sanctified with time. The more they recede into the background, the more taken for granted they become' (Willard, 1985)). The most fundamental of these is the tension that exists between *training* (and the choice of this word is quite deliberate) the future scientist and *educating* the future scientist. The former will become the producer of scientific knowledge whilst the latter will remain a critical consumer of scientific knowledge. The problem for science education is that there exists an uneasy tension between these two aspirations – that is between the needs of the minority who will continue the study of science and the needs of the majority who will not. The needs of the future scientist are met by an education which is essentially foundationalist – that is one which attempts to educate the neophyte student in all the basic concepts of the discipline. This is necessary because entering into the practice of science requires a long apprenticeship in which the conceptual foundations of the domain are acquired. For, as scientific knowledge is cumulative each generation builds on the discoveries of its forebears requiring each generation to learn more and more. The consequence is two fold: First, as Cohen (1952) has argued, is that 'all too many science courses have attempted to make students memorise a series of dry facts which no practising scientist readily memorizes such as the density of various substances, the atomic weight of different chemical elements, conversion factors from one system of units to another, the distance in light years from the Earth to various stars (and so on).' Second, because time is finite, and only a certain amount of knowledge can be acquired in a given time, science degrees become ever more specialist. Degrees in botany or zoology which provided a broad overview of major aspects of the life sciences have been replaced by degrees in genetics, molecular biology and immunology which have a narrow specialist focus. The consequence is that many scientists have a specialist education making them very proficient within their

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specialist domain but with no broad education about science.

The fundamental flaw with this approach to teaching science is that, whilst the unity and salience of such information is apparent to those who hold an overview of the domain, its significance is simply incomprehensible to the young student. Only for those who finally enter the inner sanctum of the world of the practising scientist will any sense of coherence become apparent. As a consequence only those that ever reach the end get to comprehend the wonder and beauty of the edifice that has been constructed. Or, as has been argued elsewhere:

> To borrow an architectural metaphor, it is impossible to see the whole building if we focus too closely on the individual bricks. Yet, without a change of focus, it is impossible to see whether you are looking at St Paul's Cathedral or a pile of bricks, or to appreciate what it is that makes St Paul's one of the world's great churches. In the same way, an over concentration on the detailed content of science may prevent students appreciating why Dalton's ideas about atoms, or Darwin's ideas about natural selection, are among the most powerful and significant pieces of knowledge we possess. (R. Millar & Osborne, 1998, p. 13)

In contrast to the needs of the next generation of scientists, the needs of the future citizen are different. Such individuals require more than a knowledge of the basic concepts of science but also a vision of *how* such knowledge relates to other events, *why* it is important, and *how* this particular view of the world came to be. Any science education, therefore, which focuses predominantly on the intellectual products of our scientific labour – the 'facts' of science – simply fails to offer what is required.

The phrase that is commonly used to embody this vision of science education is that we should provide an education for 'scientific literacy' – a view that Robin Millar and I articulated in the report 'Beyond 2000: Science Education for the Future' (Millar & Osborne, 1998) when we argued that:

> the primary and explicit aim of the 5-16 science curriculum should be to provide a course which can enhance 'scientific literacy', as this is necessary for all young people growing up in our society, whatever their career aspirations or aptitudes.

As many have pointed out, however, the term 'scientific literacy' has a diverse range of meanings and there is a lack of an explicit and consensually agreed articulation. My task here is to argue that through the work I and others have conducted over the past 10 years, there is an emerging consensus of both what we mean and why such an education matters.

However, before I expand on what is currently understood by education for scientific literacy, I need to convince you that the science education as practised is not appropriate for the needs of contemporary youth. The argument here is that this failure is caused by a set of seven unquestioned norms of practice or values, all of which when examined are found wanting – a set of fallacies on which contemporary practice rests. These are:

1. The foundational fallacy
2. The fallacy of coverage
3. The fallacy of a detached or value free science
4. The fallacy that science education promotes critical thinking
5. The fallacy that there is one scientific method
6. The fallacy that scientific knowledge is useful
7. The fallacy that all children should have the same science education (the homogenous fallacy)

1. The foundational fallacy

This is the fallacy that because scientific knowledge itself is difficult and hard won, learning and understanding science requires a similar process where the student's knowledge and understanding are assembled brick by brick, or fact by fact. As a consequence only those that reach the end ever get to comprehend the wonder and beauty of the edifice that has been constructed. Current practice, therefore, is rather like introducing a young child to jigsaws by giving her or him bits of a one thousand piece puzzle and hoping that they have enough to get the whole picture, rather than providing the simplified 100 piece version. In effect, although the pupils can see the microscopic detail, the sense of the whole, its relevance and its value – the things that matter to the pupil (Rowe, 1983) are lost. Chown (1998) provides a good example of a tale which the foundationalist approach offers only to undergraduates or postgraduates taking courses in stellar nucleosynthesis-the grand ideas of science which are reserved only for those who complete the course.

> But if all these examples of our cosmic connectedness fail to impress you, hold up your hand. You are looking at stardust made flesh. The iron in your blood, the calcium in your bones, the oxygen that fills your lungs each time you take a breath - all were baked in the fiery ovens deep within stars and blown into space when those stars grew old and perished. Every one of us was, quite literally, made in heaven. (Chown, 1998, p. 62)

Yet there is nothing about such a story which is intrinsically difficult. The failure to communicate such ideas in compulsory science education simply reinforces Claude Bernard's, the famous 19th century philosopher, view that science is a 'superb and dazzling hall, but one which may be reached only by passing through a long and ghastly kitchen.'

2. The fallacy of coverage

School science is suffering from a delusion that the science we offer must be both broad and balanced. The result is an attempt to offer a smattering of all sciences and to cram more and more into an oft-diminishing pot. Quite clearly, as the bounds of scientific knowledge expand from evolutionary biology to modern cosmology, more and more knowledge vies for a place on the curriculum. However, just as those teaching literature would never dream of attempting to cover the whole body of extant literature, choosing rather a range of examples to illustrate the different ways in which good literature can be produced, has the time not come to recognise that it is our responsibility to select a few of the major *explanatory* stories that the sciences offer? And surely it is the *quality of* the experience, rather than the quantity, which is the determining measure of a good science education?

3. The fallacy of a detached science

Science education persists with presenting an idealized view of science as objective, detached and value free. This is wrong on three counts. First the public, and particularly young people, do not distinguish between science and technology. Second, science is a socially-situated product and the language and metaphors it draws on are rooted in the culture and lives of the scientists who produce new knowledge. Thirdly, those that engage in science are not the dispassionate, sceptical and disinterested community that Merton (1973) portrays. Science is a social practice, engaged in by individuals who share a 'matrix of disciplinary commitments, values and research exemplars' (Delia, 1977). Within the contemporary context, where scientists are employed by industrial companies with vested interests, it is hard to advance a case that science is simply the *pursuit of truth* untainted by professional aspirations or ideological commitments. For these days scientists are judged as much by the company they keep as the data they may gather (Durant, 1999).

Finally, the separate portrayal of science from technology (in curricula and teaching) eliminates all considerations of the societal implications for society and individuals. For, as Ziman (1994) argues, if science education fails to make the small step from science to its technological applications, how can it take the much larger step to the implications for the society in which it is embedded?

4. The fallacy of critical thinking

This is an assumption that the study of science teaches students reflective, critical thinking or logical analysis which may then be applied by them to other subjects of study. It is based on the fallacious assumption that mere contact with science will imbue a sense of critical rationality by some unseen process of osmosis. It is also an assumption questioned by the Wason 4 card problem and the Wason 2, 4, 6 problem (Wason & Johnson-Laird, 1972) both of which require a standard scientific strategy of falsification to determine the correct answer and, which very few, including scientists, use.

Secondly, the notion that science develops generalizable, transferable skills is also an assumption questioned by the body of research which suggests that people's use of knowledge and reasoning is situated within a context (Brown, Collins, & Duiguid, 1989; Carraher, Carraher, & Schliemann, 1985; Lave, 1988) and that detached knowledge is of little use to individuals until it has been reworked into a form which is understood by the user. This is not to say that there are no general intellectual skills. Rather, that such skills need a knowledge base for individuals to demonstrate their capability – a knowledge base which must be acquired in a given context.

5. The fallacy of the scientific method

This is the myth that there exists a singular scientific method whereas the record of those who have made the important discoveries of the past shows not only that scientists rarely attempt any such logical procedure, but that the methods vary considerably between the sciences. The methods deployed by the palaeontologist working out in the field are about as similar to those used by the theoretical physicist as chalk and cheese. Yet the science that increasingly confronts the individual in the media, with its focus on environmental or biological issues, is predominantly based on correlational evidence and uses methodological devices such as clinical trials with blind and double-blind controls. Yet where, and when, is there any treatment of the strengths and limitations of such evidence (Bencze, 1996)? Is it not time to give up any notion that there is such a singular entity and turn instead to presenting a range of ideas about science and its working? Moreover, when so much of the science reported in the media is based on epidemiological research and associative findings – probability and likelihood rather than causal relationships and certainty – is it lot time to teach about such data, its interpretation and evaluation?

6. The fallacy of utility

This is the myth that scientific knowledge has personal utility – that it is essential to the mastery of the technology; to remedy its defects; and to live at ease in the culture of technology that surrounds us. Yet as machines become more intelligent they require less care and thought for their effective use. Even the economic value of scientific knowledge is questionable as current employment trends, at least in the UK and USA, suggest that, although we will need to sustain the present supply of scientists, there is no indication that there is any need to significantly improve the number going into science, which remains, as ever, a small minority of the school cohort of around 10- 15% (Coles, 1998; Shamos, 1995).

7. The homogeneous fallacy

Increasingly, in many countries, science education labours under the fallacy that its clientele are an entity who, whilst they might differ in aptitude and ability, nevertheless are best served by one homogeneous curriculum. With its emphasis on pure science – and then predominantly the exact sciences, a foundationalist approach, and a high-stakes assessment system, the result is too often a pedagogy based on transmission (Hacker & Rowe, 1997; Lyons, 2006). By the onset of adolescence, the imperative of relevance increasingly challenges the delayed gratification on which such a curriculum rests leading to a lack of motivation and interest (Osborne & Collins, 2001). Pupils, therefore, need to be offered a diversity of science courses to meet their disparate needs.

The effect on student attitudes

That this form of education singularly fails to engage contemporary youth in advanced societies is apparent from a growing body of research. For instance, the ROSE project (Sjøbeg & Schreiner, 2005) has surveyed students' attitudes to school science across more than 40 countries. In all developed countries, school science was found to be less popular than other school subjects (Figure 1). Indeed the effect is so pronounced that there is a 0.92 negative correlation between student's response to this question and the UN index of human development which measures factors such as GDP/capita, literacy rates and mortality statistics.

In a study undertaken with 20 focus groups in England with school students age 16 (Osborne & Collins, 2001), the negative features of such a curriculum were found to be that it was reliant on a default pedagogy of transmission consisting of too much repetition, copying notes from the board and a lack of space for students to engage personally or discursively with the subject. Students felt as if they were being force marched across the scientific landscape with no time to stand and stare.

Scientific Literacy – the goal of science education?

Bybee (1997), DeBoer (2000) and Laugksch (2000) provide brief reviews of the historical use and meanings of the term 'scientific literacy' in science curriculum writings, drawing on sources from several countries. Its first use is generally attributed to Hurd (1958), in the context of proposing goals for science education in the post-Sputnik era. At its simplest level, 'scientific literacy' is a shorthand for 'what the general public ought to know about science' (Durant, 1993, p. 129). As Bybee (1997) puts it:

> The phrase 'scientific literacy for all learners' expresses the major goal of science education – to attain society's aspirations and advance individual development within the context of science and technology. (p. 69)

DeBoer in an extensive review of the use of the term suggests that there are 9 different meanings of the term. The consequence is that the distinction between the term and science education itself becomes blurred – the two effectively becoming synonymous and little more than a rallying cry behind which those who advance the case for reform, such as myself, can unite.

However, this is not a position that I wish to espouse. Rather, Norris and Phillips (2003) in a careful analysis of the term develop a powerful argument that 'scientific literacy' must be grounded in the fundamental sense of literacy as the ability to analyse and interpret text. Science, they argue, could not exist as an oral

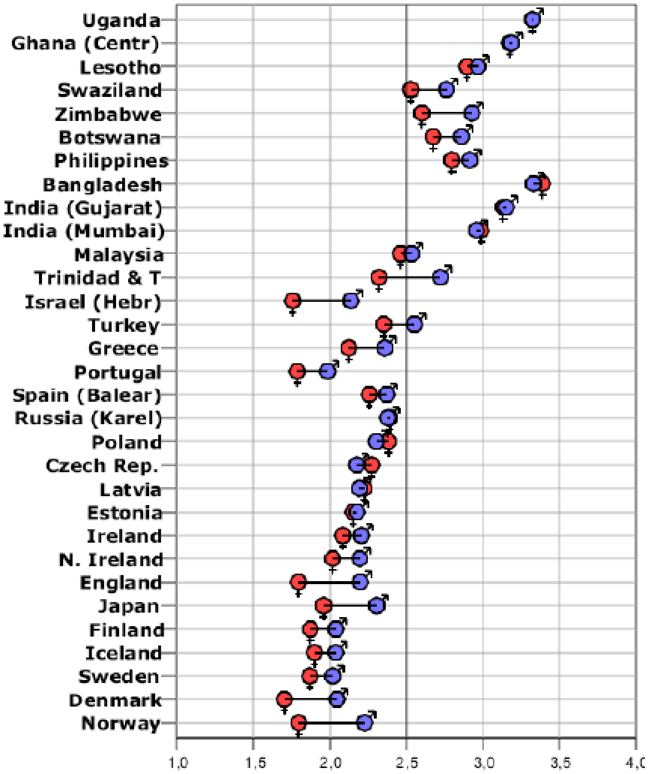

Figure 1. Student responses to the question 'I like school science more than other school subjects' on a scale of 1 (negative) to 4 (positive) (red – girls; blue-boys) (Sjoberg, 2005).

tradition; texts are essential, not optional. They are a constitutive feature of science – just as empirical data collection is. An understanding of science therefore requires the ability to read texts, and hence, literacy is at the core of scientific literacy. Together we have advanced a view of science education which sees the role of interpretation and argumentation in scientific inquiry as central (S. Norris, Phillips, & Osborne, 2006 (in press)). Interpretation is concerned with questions of meaning and explanation. Argumentation is concerned with justifications of what to conclude and what to do.

To interpret and critically evaluate writing in science and writing about science – in short to become a critical consumer of scientific knowledge, science education requires a triumvirate of a knowledge and understanding of:

a. the scientific content
b. the scientific approach to enquiry
c. science as a social enterprise – that is the social practices of the community

Such an understanding is also needed because it is science which will pose the political and moral dilemmas of the twenty first century (Financial Times Editorial, 1999; Independent Editorial, 1999). The issue of what to do about global warming, whether stem cell research should be permitted, or how we restrict the spread of viruses such as avian flu are just some examples of the contemporary dilemmas confronting our societies. Resolving these requires both a knowledgeable and a critical disposition to engage in public debate of the applications and implications of scientific advances. Without such critical engagement, public distrust of scientific expertise is in danger of placing unwarranted restrictions on future research and technological development. Fear of the worst is leading the public to demand a naïve application of the precautionary principle to scientific research potentially limiting the advancements that science may offer for solving the plethora of problems that face contemporary society.

For our future citizens, their science education should enable them to live and act with reasonable comfort and confidence in a society that is deeply influenced and shaped by the artefacts, ideas and values of science – rather than feeling excluded from a whole area of discourse, and, as a corollary marginalised. This viewpoint is most clearly expressed in the European Commission *White Paper on Education and Training* (European Commission, 1995) which argues that:

> Democracy functions by majority decision on major issues which, because of their complexity, require an increasing amount of background knowledge. … At the moment, decisions in this area are all too often based on subjective and emotional criteria, the majority lacking the general knowledge to make an informed choice. Clearly this does not mean turning everyone into a scientific expert, but enabling them to fulfil an enlightened role in making choices which affect their environment and to understand in broad terms the social implications of debates between experts. There is similarly a need to make everyone capable of making considered decisions as consumers. (pp. 11-12)

In addition, there for those of us who are committed to the notion of a liberal education as an experience that should offer access to the 'best that is worth knowing', there is a powerful argument that science represents one of the major cultural achievements of contemporary society (Cossons, 1993). Such an education would offer insights to the knowledge, practices and processes of science. In essence a science education that pursues *depth rather than breadth*, *coherence rather than fragmentation,* and *insight rather than mystification*. In such a curriculum, the study of the history of ideas and the evidence on which they are founded must lie at the core.

An Education for Scientific Literacy

Any education in science – whatever its primary goals consists of four elements: the conceptual which builds students understanding of the knowledge and ideas of science; the cognitive which attempts to develop students' ability to reason critically in a scientific manner; 'ideas-about-science' which is an attempt to develop students' understanding of both the epistemic – how we know what we know – and the processes, values and implications of scientific knowledge; and the social and affective which attempts to develop students ability to work collaboratively and to offer an engaging and stimulating experience. In a course which attempts to develop the notion of scientific literacy that I have elaborated, what might these elements address?

Conceptual

Science provides the best explanations of the material world that we have. It is those explanations that have rid us of myriad diseases such as smallpox, diptheria, tuberculosis, polio and others. The discovery of penicillin has saved at least a million lives in the UK alone and across the world an order of magnitude more. It is these explanations that have built the planes, trains and cars which permeate contemporary life and the information technology which sustains it. More importantly, it is this knowledge which will help us meet the challenges posed by global warming, growing world population and environmental degradation. This is not to argue for any kind of scientism – but rather to make the case that the knowledge generated by science is one of the major cultural achievements of Western societies in the past 400 years and its impact on our daily lives has been profound. As such it is a major foundation of our societies, and therefore, it is an essential aspect of any education that seeks to pass on its cultural heritage to the next generation. This view is essentially akin to that which, at least in English speaking countries, requires some knowledge and understanding of Shakespeare to be offered to all students because the metaphors and language of Shakespeare so permeate our common culture that those who lack knowledge of them are culturally deprived unable to participate fully in the discourse of daily life.

But accepting the argument that some conceptual knowledge of science raises another question – a question which so far has had only one answer. This is exactly what kind of conceptual knowledge is appropriate for today's world? This question must be asked and answered for several reasons.

First, scientific knowledge would appear to follow some form of Moore's Law. Moore was the man who predicted in 1965 that there would be a doubling in the density of transistors on a silicon chip every 24 months. Likewise, scientific knowledge in the past 40 years has advanced apace. Whilst we might see the development of scientific knowledge as resting on a set of stepping stones consisting of the major scientific discoveries of the past 200 years, contemporary students see the significance of scientific knowledge as residing in the objects and ideas that surround them. Consequently, there is a growing gulf between the landscape of school science – science-as-it-is-taught and the features of contemporary science – science-as-it-is-practised. How then, can the content of school science present itself as the science of today rather than the science of yesteryear?

The problem is not that science does not have narratives to tell. It is that they are not told. The challenge for us all then, is how are those narratives to be told in a manner that provides the key message first and the detail second. For instance, that you look like your parents because every cell in your body carries a chemically coded message of how to reproduce yourself. That we live on a small planet orbiting a very ordinary star half way through its lifetime. Or that all matter in the Universe consists of just 92 elements. Moreover, these messages need to be situated in contemporary contexts – the science of air pollution, genetic modification and astrophysics.

Cognitive

Let me move to the second of my goals for the teaching of science. This is developing the ability to reason. Few would deny that this is important. Not only that but the form of reasoning developed by science lies at the heart of Western rationality. For at its core, scientific thinking is based on a commitment to evidence as the means of adjudicating competing knowledge claims. Thus when a major disaster such as the recent Tsunami occurs, we no longer ascribe such events to unfortunate acts of God but look for mechanistic explanations which are justified by scientific evidence.

Now reasoning in science uses particular forms of argument. Argumentation is a verbal, social, and rational activity aimed at convincing a reasonable critic of the acceptability of a standpoint by putting forward a constellation of one or more propositions to justify this standpoint (van Eemeren, Grootendorst, & Henkemans, 2002). Current research into the activities of scientists shows that argument is a central feature of the resolution of scientific controversies (Fuller, 1997; Taylor, 1996). Although the final reports that appear in journals and textbooks may typically portray science as purely analytical and logical, studies of science in the making (e.g., laboratory studies) demonstrate that much of science involves dialectical and rhetorical argumentation in writing, research, and the production of knowledge (Latour & Woolgar, 1986; Sutton, 1992). Scientists devote their energies to persuading others that what they have perceived is important and that their interpretations are valid (Cunningham & Helms, 1998).

Yet if argument is the predominant form of critical thinking in science, science education itself has paid it little attention. Although many have highlighted the importance of argument for providing opportunities to learn about science, not merely science content (Driver, Newton, & Osborne, 2000; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000), to make students' scientific thinking and reasoning more visible (Bell & Linn, 2000; Chinn & Anderson, 1998), and to support students in developing scientific thinking (Kuhn, 1992, 1993; Kuhn, Shaw, & Felton, 1997).

Arguments in science are dependent of particular forms of reasoning. They may be causal as in explaining why rainbows appear only when it is raining and the sun is shining; they may depend on notions of covariation as in explaining how force and acceleration are related; they may be correlational as in justifying why smoking is likely to cause lung cancer; or they may be probabilistic such as when justifying the likely outcome of a thousand throws of a dice or the result of crossbreeding two different coloured varieties of the same plant.

However, how do we develop the cognitive abilities of students to engage in these forms of critical thinking? The correlate of the argument that learning science means learning to talk science *is that* learning to reason scientifically means asking students to reason scientifically. In the case of empirical work, observation of science lessons in England indicated that much of the time spent on practical work is devoted to carrying out the practical procedures themselves (Newton, Driver, & Osborne, 1999). Some studies found that the fundamental concern of many students in the laboratory is just completion of the given task (Berry, Mulhall, Loughran, & Gunstone, 1999; Edmondson & Novak, 1993). In Korea, a survey of the features of practical work in physics in middle school science textbooks reported that only 3% of the practical work was intended to help students to learn how to use data to support a conclusion and only 9.5% on learning to communicate the results of their work (Kim, Kang, & Song, 2003). Indeed Watson et al (2004) found that there was virtually no argumentative discourse present in any of the work conducted in a set of science lessons whose discourse examined exhaustively.

Hence, if we want our students to develop the ability to think critically about scientific evidence, then we must offer them that opportunity. In particular we must break the tie so strongly embedded in the cultural habitus of teaching science that the primary task is to persuade students of the validity of the scientific world view – where experiments are performed simply to confirm the theoretical predictions elaborated by the teacher. Students need the opportunity to consider data which has no clear interpretation and to consider plural alternatives. Simply presenting scientific knowledge as a body of authoritative knowledge which is to be accepted and believed means that the contemporary science classroom has, ironically, is still firmly rooted in pre-Enlightenment times where:

> 'the grounds for accepting the models proposed by the scientist is often no different from the young African villager's ground for accepting the models propounded by one of his elders. In both cases the propounders are deferred to as the accredited agents of tradition. ... For all the apparent up-to-dateness of the content of his world-view, the modern Western layman is rarely more 'open' or scientific in his outlook than is the traditional African villager.' (Horton, 1971)

Ideas-About-Science

What is it about the manner in which scientific knowledge is produced that makes it reliable knowledge? How do we know what we know and why it should be valued? Understanding the epistemic aspect of science is an essential part of any comprehensive science education. That it is currently underemphasised comes from asking what at first place seems to be the simplest of questions 'How do we know that day and night are caused by a spinning Earth? This so-called trivial piece of knowledge is such a commonplace that it is included in primary school science curricula. The lack of response reveals the shallow foundations on which so much of our knowledge rests. Why, you might ask, should it be believed? After all, there are good arguments against.

- If the Earth was spinning, you should not land on the same spot.
- If it is spinning, once a day, the speed at the equator is over 1000 miles an hour which should fling most people rapidly into space.
- And, surely, at that speed, there should be the most enormous wind as the earth runs ahead of the atmosphere which drags behind.

The empirical evidence for our beliefs was first demonstrated by Foucault in 1851 in the Pantheon in Paris. Other evidence comes from long exposure photographs of the night sky showing all the stars appearing to rotate around the pole star. The scientific explanation stands because (a) it is impossible to refute such evidence and (b) we can justify why the arguments for a moving Sun are wrong. Scientific literacy depends as much on the ability to refute and recognise poor scientific arguments as much as it does on the ability to reproduce the correct scientific view. Argument is, therefore, a core feature of science and, as a corollary, should be a distinctive feature of any science education (Driver et al., 2000; Newton et al., 1999).

More fundamentally, there is a moral case for the epistemic basis of belief to be a significant feature of any science education (Norris, 1997):

> To ask of other human beings that they accept and memorize what the science teacher says, without any concern for the meaning and justification of what is said, is to treat those human beings with disrespect and is to show insufficient care for their welfare. It treats them with a disrespect, because students exist on a moral par with their teachers, and therefore have a right to expect from their teachers reasons for what the teachers wish them to believe. It shows insufficient care for the welfare of students, because possessing beliefs that one is unable to justify is poor currency when one needs beliefs that can reliably guide action.

Exploring the ways in which scientific knowledge is obtained, checked and refined raises other issues about other aspects of the nature of science that should be a feature of an education for scientific literacy. There is now an emerging consensus from both our work (Osborne, Ratcliffe, Collins, Millar, & Duschl, 2003) and others (McComas, 1998) that the following features should be essential elements of any compulsory school science education.

Scientific methods and Critical Testing;
The Creative nature of scientific work;
Historical development of Scientific Knowledge;
Science and Questioning;
Diversity of scientific thinking;
Analysis and Interpretation of data;
Science & Certainty;
Hypothesis and Prediction;
Cooperation and Collaboration.

Only through exploring such aspects will students be introduced to the idea that the scientific community is a highly moral community; that scientists report their findings through conferences and journals; that scientific findings are only accepted once they have been evaluated critically by other scientists; that explanations are not simply derived from the data; that two scientists may legitimately come to different conclusions from the same data or may be influenced by his or her interests; and that they are rarely immediately abandoned when confronted by anomalous data.

Moreover, secondary science must offer some opportunity to discuss and explore the meaning of the concepts that it is attempting to explain, and their social implications. Here again is a pupil articulating that view:

> Like this morning we were talking about genetic engineering and Miss told us about this article, about how they're going to make clones of each baby that gets born. They're going to make a clone of it – so say if it needs a transplant, kidney transplant or whatever he could get if from his clone. And she didn't want to hear that it is wrong. She didn't want to know our opinions and I don't reckon that the curriculum lets them – lets us discuss it further. I mean science- okay – you can accept the facts, but is it right, are we allowed to do this to human beings.

Exploring such issues also requires developing a better understanding of risk – that nothing is risk free and that new technologies or new medicines often have unknown risks associated with them. In addition that the mechanisms for assessing risks are too reliant on one feature of statistics – mortality rates rather than reflecting less minor injuries. And that individuals are often make poor judgements of risk, over assessing unfamiliar risks and under assessing familiar risks (Adams, 1995). The goal here is to make students aware that risk is an inherent feature of life and to improve students' ability to make better assessments of what risks are acceptable.

Social & Affective

However, all of this argument is of little value if it fails to address the social and affective component of science education. In short, how do we ensure that what we offer is intellectually engaging and appealing? Undoubtedly, science offers insights into the material world that generate a sense of awe and wonder. A sense of awe and wonder which is captured by the following quotation:

> We learnt all these amazing things in year 7 that we'd never heard of before, like molecules and atoms and electrons. I don't know about you guys but I got really excited about it, I rushed home and told my mum about it.

Contemporary science education must also recognise the theoretical and empirical evidence which see knowledge and understanding as something which is developed, at least in part, through dialogue. This perspective, rooted in the work of Bakhtin and Vygotsky, sees dialogic interaction as a means by which students can construct meaning not only from the interplay of new experiences with what they already know, but also from discursive interaction with their peers or teachers. Such dialogue, when appropriately scaffolded by their teachers, enables students to work in the zone of proximal development and internalise meanings which are developed and constructed interpersonally to form new understandings intra-personally (Vygotsky, 1962). Dialogic enquiry is central to learning as it demands the use of the epistemic processes – describing, explaining, predicting, arguing, critiquing, explicating and defining (Ohlssson, 1996) – all of which are central to science and all of which are features of dialogic interaction. A dialogic approach to pedagogy therefore seeks to develop a classroom environment which is *collective* in that teachers and children address learning tasks together; *reciprocal* in that teachers and children listen to each other and consider alternative viewpoints; *supportive* in that children articulate their ideas freely helping each other to reach common understandings; *cumulative* in that teachers and children build on their own and each others' ideas; and *purposeful* in that teachers plan and facilitate dialogic teaching with well-defined educational goals in view (Alexander, 2005).

The value of such an approach for students' affective response comes from research by Nolen (2003) who studied the relationship between 322 ninth grade school students' perception of the classroom environment and their motivation, learning strategies, and achievement. Her findings showed that 'students in science classrooms where teachers were perceived to endorse independent scientific thinking and to desire deep understanding of science concepts had higher achievement and greater satisfaction with their science learning.' Likewise the research of Osborne and Collins (2001) found that the lack of opportunity to explore and discuss ideas in science was one of the reasons that students cited for their disaffection with school science.

Toward Science Education for the Twenty First Century

Any teaching and learning situation is a product of three elements – curriculum, pedagogy and assessment. In the case of the curriculum, the major development within the UK is of a course aptly called *Twenty First Century Science* whose rationale and content has been fully articulated by Millar (2005). The basic principle of this course has been to break the knot that ties school education to serving the dual function of educating all students for citizenship and, simultaneously, educating the next generation of scientists. This has been achieved by designing a course which explicitly addresses science for citizenship in the belief that all students will benefit from a broad education about science. The course has two key components – a set of explanatory themes (the content of science) and a set of ‘ideas-about-science’ which are addressed through topics such as air pollution, food matters, you and your genes, Earth in the Universe and more.

Students can then choose to do additional academic science, a course in applied science or, alternatively, no more science whatsoever. Preliminary data that we have gathered for the evaluation of this course would suggest that it is perceived by teachers as being a more enjoyable course to teach, by students as significantly more relevant and topical, and has led to more students expressing the intention to sustain the study of science post 16. Nevertheless, the difference is not significant and it would be a mistake to think that a change in the curriculum will lead to a substantive change in the uptake of science. Especially when all the research points to the fact that it is teacher quality which is the biggest determinant of student engagement with science (Osborne, Simon, & Collins, 2003).

Changing the curriculum is one thing. Asking teachers to change their pedagogy to meet the demands of such a curriculum is another. The evaluation conducted of the innovative post-16 *Science for Public Understanding* Course (Osborne, Duschl, & Fairbrother, 2002) found that whilst the course was successful in sustaining and developing student enjoyment of, and interest in, science, teachers struggled to adapt their pedagogy. For too often

> teachers found it difficult to break free of the modes of interaction with students that are acquired by teaching standard science courses. Too many lessons were observed where explaining the science predominated to the detriment of exploring other aspects of science, in particular the ideas-about-science component and the underlying major science explanations.

For instance, the use of small group discussion was not a technique that was widely used. This quotation beneath, drawn from an interview with teachers of the course, illustrates the nature of the problem.

> **Teacher**: Um. Discussion in small groups, umm it’s a fairly small group anyway. Yeh I have done that but tend not to.
>
> **Int**: Because?
>
> **Teacher**: It’s … I don’t know really. It’s just that … the type of topics don’t necessarily lend themselves to small group discussions. I mean I have done it once or twice. Whole class discussions I find better.
>
> (Male experienced biology teacher, girls’ grammar school)

Likewise, in another project (Bartholomew, Osborne, & Ratcliffe, 2004) where we worked with a group of twelve teachers to explore how some of the ideas-about-science emerging from our Delphi study (Osborne et al., 2003) of what should be taught about science, similar difficulties were found. There was, however, an enormous diversity of practice. Hence, we began to ask ourselves what characterised these differences. From a repetitive reading of the data we came to the view that these could be characterised in terms of a set of 5 dimensions (Fig 2).

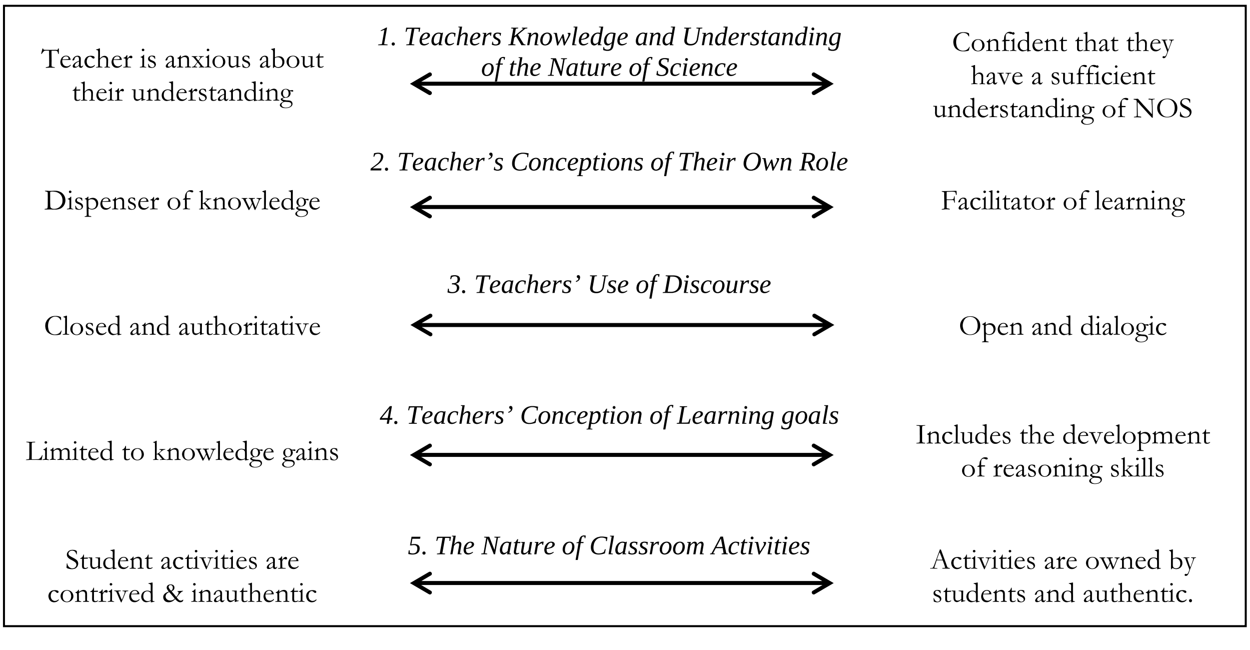

Figure 2. The 5 Dimensions of Practice that influence teachers’ pedagogy when teaching about science.

Those teachers who appeared to us to be more successful at generating activities that opened up the discourse space for students to develop their knowledge and understanding of ideas about science lay to the right on this spectrum. Thus, it is not enough just to transform the curriculum; we must also transform teacher's pedagogy. The teaching of school science has become habituated to one where science is taught as dogma and not as a body of knowledge to be approached, discussed and evaluated.

Finally, we have to remember that there is a third component to transforming the teaching of science. Practice is a combination of the triumvirate of curriculum, pedagogy, *and* assessment. So far, the research community has displayed far less interest in this component than we have in the other two. However, in a context of increasing accountability, it is to assessment that teachers look for the intended curriculum, not the curriculum itself. There is some limited work that has been undertaken such as the Iowa Assessment Handbook (Enger & Yager, 1998) which is a compilation of items that assess the understanding of science in 6 domains – one of which is the nature of science. However, there is no statistical data to suggest that the reliability or the discrimination of these items have been tested. A small scale project to explore different ways of assessing 'ideas-about-science' was undertaken by Osborne and Ratcliffe (2002). The nature of this work was essentially exploratory and produced a range of items some of which were effective and some which were statistically less reliable. We see this work as the first step of a much larger project which needs to develop a range of generic frameworks for assessing student understanding of ideas-about-science. Some of this knowledge of effective means of assessment will emerge through the work that examiners undertake to develop items for the summative and terminal course examinations. The problem is simply that the science education community currently lacks the body of knowledge or 'know-how' to assess student understanding effectively and efficiently at a desirable level. The primary goal of this work is to develop schemes of assessment which have, at worst, a benign effect on the curriculum.

Only an approach that interrelates these three elements – curriculum, pedagogy and assessment – can ensure that students are offered a fundamentally different experience from that which currently predominates throughout the world. It is the need to recognise that these elements cannot be seen in isolation, that developing assessment items is not an afterthought, and that we must take a more holistic view of curriculum change to achieve a science education for the twenty first century. In the words of E. M. Forster – 'only connect, the prose and the passion, and both will be exalted, and human love will be seen at its height. Live in fragments no longer.'

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