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Towards a science curriculum for public understanding

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A frequent justification for 'science for all' is in terms of the need to improve scientific literacy and promote better public understanding of science. But there is much evidence that many school students and adults have little understanding of basic science ideas or processes. The five-year moratorium on change following the Dearing review of the National Curriculum provides an opportunity for a fundamental review, by science educators, of the structure and content of the science curriculum, as a vehicle for promoting public understanding.

CONCERNS ABOUT SCIENCE EDUCATION

Within the past ten years, science has joined English and mathematics as core subjects in the school curriculum in the UK. There appears to be broad consensus, both within the education system and beyond, that all children should study science throughout the period of compulsory schooling, from 5-16. There has been little opposition within schools or beyond to this increase in prominence of science or to its allocation of 20% of curriculum time at Key Stage 4, double that for other subjects.

Amongst the rare dissenting voices, Chapman [1] has written of 'The overselling of science education in the 1980s, contesting the validity of arguments for compulsory 'science for all'. From outside the science education community, Simon Jenkins [2], in a strongly written piece in *The Times*, argues that 'the adult world does not require deep knowledge of maths and science', and that the importance attributed to these subjects by politicians and industrialists is the result of a 'confidence-trick' played by the academic science community. Although outspoken critiques of this sort are relatively few, they are, I think, the visible sign of a wider and more general unease and concern about science education provision.

A major cause of this unease is the accumulation of evidence - not just in Britain but throughout much of the developed world - that little scientific understanding is actually assimilated by most students. The APU studies [3] showed that only around 35% of 15 year olds could apply scientific knowledge to simple problem situations. Research into students' learning in specific science domains points in the same direction: very few young people by the age of 16 have a solid grasp of even the most basic scientific facts, principles, concepts and ideas. Ideas like the particulate theory of matter, the scientific model of the solar system, gas exchanges in plants and animals - all are poorly understood and there are many common and persistent misconceptions [4].

A recent television programme (broadcast on BBC2 in September 1994), based on current work at Harvard and Leeds Universities, illustrated this dramatically, showing American engineering graduates unable to explain where the matter came from in a block of wood - and reluctant to accept that it could possibly have come from carbon dioxide in the air. The same research showed that students' lack of understanding of basics is apparently not noticed by their teachers, who consistently over-estimate their own students' understanding of basic ideas following instruction - perhaps because students find it possible despite this to obtain reasonable scores on conventional tests and examinations. Surveys of science understanding amongst the adult population [5] show much the same picture: little understanding and many potentially serious misunderstandings of basic science ideas.

Some have argued that the lack of effectiveness of science teaching is a consequence of the content of the curriculum on offer. Claxton [6] writes of his:

> growing realization that we do not have a problem with science education; we have a disaster with it. Reading the literature, talking to teachers and students, and sitting in lessons, ... it becomes obvious that what was being offered missed the mark of what the majority of students needed and wanted to know, not just by a bit but by a mile (p vii).

Do many students achieve little in science because they simply cannot see the point of it? And might their verdict be, as Jenkins argues, substantially correct?

To these I would add a third area of concern, about the uniform and unrelenting pace of most science programmes. Each lesson builds on the last, introducing new ideas. The 'big ideas' get lost in the mass of detail. For many students it is simply 'one thing after another; before you have fully grasped one idea you are on to another. There is no variety of pace, little time for consolidation, no learning 'rhythm', just, for most students, an out-of-control roller-coaster of ideas.

In England and Wales, we have seen a succession of changes in the science curriculum over the past eight years, many of them planned and introduced in haste. Now we are promised a five-year period of consolidation. It is important that this interval be used to reflect on the purposes and structure of the science curriculum in preparation for the next review, when it arrives. In this article I want to explore two questions:

- Why should science be taught to all school students?
- And (in the light of answers to that question) what should the science curriculum look like?

WHY TEACH SCIENCE, AND WHY TO ALL?

In the first *ASE Science Teachers' Handbook*, Milner [7] addresses the question 'why teach science and why to all?' He argues that science, or for that matter any subject, can only lay claim to a place in the curriculum if we can show three things about it:

1 That it contributes distinctive skills, concepts and perspectives, not offered by any other subject.
2 That these would not be acquired informally, but only through formal instruction.
3 That it is important and of value to acquire them.

The first can be readily granted. Science has a distinctive area of concern - the behaviour of the natural world - and uses distinctive concepts and ideas to express our understanding. And there are distinctive features of its approach to enquiry, though these are not easy to specify in detail.

Scientific knowledge also meets the second criterion. It is very clear that many of the major ideas of science are counter-intuitive, as Wolpert, for example, has recently argued [8]; they are not simply acquired through experience. Teachers' experience of the problems of 'discovery learning' and of the persistence of misconceptions and 'alternative conceptions' despite evidence which conflicts are persuasive evidence that this is so. The second criterion, however, may be more significant as regards so-called processes of science: I have argued elsewhere [9] that 'process skills' such as observing, classifying, predicting and so on *are* acquired informally - indeed are used by children from a very early age - and that the issue for science education is not teaching or developing these, but encouraging students to *use* capabilities they already possess in exploring scientific questions.

The third condition, that science is important and of value, raises the questions 'important and of value to whom?' and 'for what?'. Milner lays out a number of ways in which science is important and of value both to the individual leaner and to society.

Intrinsic justification

Scientific knowledge is a cultural product of great intellectual power and beauty. Humans have a curiosity about the natural world which scientific knowledge can help to satisfy. Many people have found the pursuit of science personally satisfying and rewarding.

instrumental justification

Scientific knowledge is necessary in order to:

- make informed practical decisions about everyday matters;
- participate in decision-making on issues which have a scientific/technological component;
- work in jobs which involve science and technology (at various levels)

Thomas and Durant [10] approach the same question from a rather different perspective, in an article entitled: 'Why should we promote the public understanding of science?' They set out the different arguments which can be found in the literature on public understanding. These can be grouped into five distinct categories.

①The economic argument: that there is a connection between the level of public understanding of science and the nation's economic wealth. In addition, scientific and technical achievement is seen as a sign of a nation's international standing. Maintaining this depends on a steady supply of technically and scientifically qualified personnel.

②The utility argument: that an understanding of science and technology is practically useful, especially to anyone living in a scientifically and technologically sophisticated society. They are better equipped to make decisions about diet, health, safety, and so on, to evaluate manufacturers' claims and make sensible consumer choices.

③The democratic argument: that an understanding of science is necessary if any individual is to participate in discussion, debate and decision-making about issues which have a scientific component. Decisions have to be made about transport, energy policy, testing of drugs and treatments, disposal of wastes, and so on. There should be public accountability about the directions of some scientific research, and public involvement in decisions about whether or not to apply such knowledge.

④The social argument: that it is important to maintain links between science and the wider culture. Specialization and the increasingly technical nature of modern science is seen as a social problem, leading to incipient fragmentation - and the alienation of much of the public from science and technology. A related argument is advanced from the science side: that improved public understanding will lead to more sympathy with, and hence greater support for, science and technology itself.

⑤The cultural argument: that science is a major - indeed, *the* major - achievement of our culture and that all young people should be enabled to understand and to appreciate it. We should celebrate science as a cultural product.

These five arguments correspond closely to the justifications offered by Milner. I have simply stated the arguments above. In the next section, I want to look at them more critically, and use them to develop criteria for decisions about the science curriculum.

CONSIDERING THE ARGUMENTS FOR TEACHING SCIENCE

Before considering each of the five arguments identified above, it is important to acknowledge that the school science curriculum has to do two jobs. For only a minority of young people, school science from 5-16 is the first stage of their training as scientists. They will go on to more advanced courses and perhaps to careers which involve science. For them, the 5-16 programme must provide a satisfactory basis for further study. The majority, however, will not study science further. For them, science is part of their general education, part of their preparation for life in a modern technical, industrialised democracy.

The science curriculum functions as:

* first stages of a training in science — for a minority

access to basic scientific literacy * — for the majority

At present in the UK, as in most other countries, the same science curriculum has to serve both ends. But it is far from clear that any one curriculum can do both these jobs effectively. It is, however, fairly clear that the present curriculum has evolved, in a fairly seamless line of descent, from curricula designed for training in science. National Curriculum science is the son (or daughter) of GCSE science, and the grandson/daughter of GCE O-level science. It has changed at the margins, some topics have been trimmed a little, it is less formal and mathematical - but its ancestry is clear. We have, in effect, assumed, through the period of comprehensivization and the ending of the GCE/CSE divide, that the route to a science curriculum for all was essentially to modify the training in science curriculum to make it more accessible.

The result has been to make the 5-16 science curriculum less suitable as a preparation for more advanced study, whilst largely failing to make it motivating or accessible to the majority. The evidence for the former is the reducing proportion of students choosing to study science, particularly physics, in post-compulsory education, and the growing (and largely justifiable) perception that post-16 science is a difficult option, involving a considerable step-up in difficulty from pre-16 courses; and, for the latter, the low levels of understanding of basic science discussed earlier. The present curriculum falls between two stools; it is unsuited to either of its purposes.

Rather than considering further piecemeal modification, I think we need to ask: what would the science curriculum look like if it were designed with the needs of the majority in mind? What would a science curriculum designed to promote scientific literacy for the majority look like? These are the questions that I want to focus on in considering the five arguments for teaching science. Later, as a separate question, we might wish to ask: would such a curriculum also be a reasonable preparation for further study in science for the minority who so chose?

The economic argument

The economic argument points to the connection between science and technology and industrial wealth-creation, and to the need for a continuing supply of science specialists to maintain and develop the technological infrastructure. This is a strong argument for making a 'training in science' curriculum available to *some* students, but, as relatively few highly trained scientists are needed, it does not, as Chapman [1] argues in detail, provide good grounds for teaching science to *all* students to age 16. The case for promoting public understanding of science will have to be made, and indeed is usually made, in terms of the other four arguments: the utility argument, the democratic argument, the social argument and the cultural argument.

The utility argument

The utility argument is that scientific knowledge is necessary for coping with aspects of everyday life. But most pieces of technical equipment can be used with little understanding of how they function and technological advance tends to make such understanding gradually less (rather than more) necessary. Few practical decisions are taken primarily on the basis of scientific understanding. When scientific knowledge is used in everyday settings, it is usually encapsulated in the form of a simple rule of thumb, like 'metals conduct', or 'if an electrical device stops working, it's probably a broken connection'. Layton [11] shows how scientific knowledge invariably has to be reworked and reconstructed to enable it to be used to guide practical action.

There is also no evidence, so far as I know, that physicists have fewer road accidents because they understand Newton's Laws of Motion, or that they insulate their houses better than other comparable social groups because they understand the laws of thermodynamics. A study of Leeds pensioners [12] showed, not surprisingly, that their decisions about heating their homes were based on a host of factors, many of which were social, and not solely on their understanding of heat loss and insulation, which was frequently over-ridden by other practical and aesthetic considerations. These examples do not, of course, argue that no piece of scientific knowledge is ever practically useful. But they do suggest that the utility argument for understanding science is overrated.

Perhaps a utility argument can be constructed on a weaker interpretation of 'usefulness'. It might be argued that some understanding of how artefacts work, and even of natural phenomena, makes one feel more knowledgeable, and hence more 'comfortable' in everyday life. Indeed explanations of this sort feature prominently in popular science publications and appear to be quite widely seen as part of scientific literacy. It is, however, difficult to argue that an interest in such matters is more valuable, either to the individual or to society, than many of the other interests that people might have. Such an interpretation of 'utility' could scarcely justify compulsory science for all.

The value, I think, of the utility argument is that it challenges us to take the criterion of 'usefulness' of knowledge seriously. It points towards a science curriculum with a much stronger emphasis on a technological way-of-knowing about phenomena, on more immediately applicable knowledge rather than abstract general principles.

The democratic argument

The democratic argument is that an understanding of science is necessary to participate in discussion, debate and decision-making about science-related issues in society. Here again there are problems if we push this claim too far. First we need to ask: what level of understanding is necessary if we are not to trivialize the issues? Even practising scientists often recognize that they are not well enough informed about an issue outside their own specialist area of science to take a firm view. Second there is the sheer number of issues. Can we really prepare young people to hold an informed view on genetic engineering, embryo research, nuclear power, disposal of toxic substances, the health risks of saturated or unsaturated fats in the diet, the possible dangers of living close to high tension power lines, and so on? Even if we could, can we anticipate the new issues that will arise during their lifetime? As the answer is surely no, are we then claiming that there is something transferable that students can learn by studying some of these issues, which will better equip them to deal with others in the future? If so, then we should try to spell out what this transferable core is.

The democratic argument points, I think, not to rather vague and ill-defined aims about developing 'decision-making skills' or 'increasing awareness of science in society', but rather to the need to give curriculum priority to *fundamental understanding* on which the more detailed knowledge needed to grasp particular issues can be built, if and when it is needed. We will return later to the question of what these 'fundamental understandings' might be.

The cultural and social arguments

The cultural argument is that science is a major achievement of our culture which all young people should therefore be helped to understand and to appreciate. The curriculum justification for science then becomes similar to that for literature, art or music. It might be argued that the cultural argument for science is stronger than for these; science is not just a major cultural achievement - it is *the* defining product of our culture, the thing which we can most confidently expect the historians and even archaeologists of the future to identify as characteristic of our time. And, as Midgley [13] argues:

> Any system of thought playing the huge part that science now plays in our lives must also shape our guiding myths and colour our imaginations profoundly. It is not just a useful tool. (p 1)

It would surely be a strange culture indeed that did not wish to pass on its most prominent thought-system to new generations. The problem for science educators is that we have not really thought out, I would suggest, what it would mean to teach, say, Newton's law of universal gravitation, or Lavoisier's discovery of oxygen, or the discovery of microbes by the early microscopists as cultural landmarks, rather than as useful knowledge or as illustration of scientific enquiry methods.

The social argument is closely related to the cultural one. It is that it is important for social cohesion to maintain links between science and the wider culture. Science in the twentieth century has become increasingly remote and technical, and difficult for the layman to understand. The gulf between science and the rest of the culture threatens the health of both. Whilst we may agree that this is a concern, it does not lead very obviously to any specific criteria for science curriculum design. We might, though, note that 'reading-about-science' has never been regarded as an important part of the curriculum. We may be neglecting a powerful educational resource in constructing a model of the science curriculum which gives little or no role to the writings of authors like Stephen Jay Gould, Paul Davies, Richard Dawkins or Primo Levi.

TOWARDS A SCIENCE CURRICULUM FOR PUBLIC UNDERSTANDING

To summarize the discussion in the preceding section, I have argued that the utility argument points to a more technological emphasis in the science curriculum, that the democratic argument implies a need to focus on fundamental understandings which provide a basis for the learning of specific details when these are required, and that the cultural importance of science provides a strong argument for introducing all students to some of the major advances in our understanding of the world, seen as significant cultural events and achievements to be celebrated.

I now want to consider the form of science curriculum to which this might lead, looking in turn at each of three aspects of an understanding of science:

- understanding of *science content* (or substantive scientific knowledge);
- understanding of the *methods of enquiry* used in science;
- understanding of *science as a social enterprise*.

Understanding science content

What substantive science knowledge should be included in a science curriculum for public understanding? Whilst it is fashionable to scorn a simple 'deficit model' of public understanding - the idea that the 'problem' is simply that people don't have enough substantive science knowledge - it is surely the case that no one could be regarded as scientifically literate without some understanding of some science content. But what content?

Given the evidence of students' lack of understanding in so many basic areas, the guiding principle as regards curriculum content must surely be: do less but do it better. It is almost a commonplace to observe that the science curriculum is overloaded. As a result, it is unclear about its priorities; students (and perhaps also teachers) are unable to see the wood for the trees. The plethora of textbooks, curriculum packages and syllabuses conveys an impression of lack of consensus about priorities, and about structure. What is central? What really matters?

I would suggest that the science curriculum from 5-16 should have two aims as regards science content:

- to help students become more capable in their interactions with the material world, by emphasizing a practically useful, technological way-of-knowing;

- gradually to develop students' understandings of a small number of powerful 'mental models' (or 'stories') about the behaviour of the natural world.

There is not space in this article to develop either of these ideas thoroughly, but I will try to use a few examples to illustrate what I have in mind.

A more technological emphasis

Take energy as an example - a concept which is rightly regarded as one of the great achievements of science. The problem is that the scientific energy concept is simply too abstract and difficult for most students up to 16. We might do better if we based our curriculum treatment on the everyday meaning of energy, which is essentially synonymous with 'fuel' - something which is used up in processes, makes things happen, is valuable and in limited supply and so should be used sparingly. The curriculum would focus on useful ideas like fuel use and fuel efficiency. Ideas about insulation could be based on a simple 'caloric' model of energy, which is useful (and widely used by engineers) in this context.

Similarly, many students can cope admirably with a technological way-of-knowing about simple electric circuits, using ideas about closed loops to make circuits to switch things on and off as required, and variable resistors to control brightness of bulbs or speed of motors. But they quickly become lost in the theoretical model of current, voltage and resistance. Even practising electricians and repair men rarely use the formal model, but base their understanding on more pragmatic models and rules of thumb. In mechanics, a technological approach might include the uses of levers, gears and pulleys, and could explore friction and air-resistance in relation to real practical problems, without introducing the difficult and counter-intuitive idea of inertia.

These ideas are far from exhaustive. They are intended only as illustrations of topics where a significantly different approach might be adopted. There are other topics and perhaps also some new topics, such as information, where a technological way-of-knowing might be a more appropriate curriculum aim than an abstract theoretical understanding.

This may also be the place to acknowledge that there is a place, perhaps even a need, in the science curriculum for a small amount of what might be termed 'scientific general knowledge'. For example, it may be important for students to know that metals come from ores which are mined from the Earth's crust, and that plastics are made (largely) from oil - without necessarily knowing much about the processes or chemical reactions, involved.

Powerful models

Models are important because they are at the heart of science as an intellectual endeavour. The central aim of science is to provide explanations for natural phenomena; the form these explanations take is of a 'story', or 'mental model', which provides a means of thinking about what is going on, accounting for the things we have observed, and imagining how things might turn out in new situations.

Models of this sort are, however, rarely directly applicable to everyday situations. Their inclusion in the curriculum cannot be justified by a simple appeal to the utility argument, though they may, of course, provide the understanding for actions we carry out on the basis of trust, for example, when we follow medical advice about a course of treatment, or about changing our diet. Some models also provide the basic understanding which is essential for getting to grips with many key issues involving the application of science. They do not, of themselves, provide all we need to know to reach an informed view on the issue; but without the basic understanding they provide, it is hard to see how any rational understanding is possible. So, for example, Andersson [14] shows how an understanding of the possible effects of pollution from vehicle exhausts depends on an understanding of the scientific model of a chemical reaction.

Therefore, he argues:

> The concepts used here - atom, molecule, chemical reaction - should be part of the mental equipment of every pupil by the time he or she leaves school. They are key concepts that help build a rough model of various situations, for examples, one's own working environment. These concepts enable us to form a general picture and provide a basis for further enquiry about the details. (pp 53-4)

Some models, on the other hand, like the scientific model of the solar system, have little practical utility, nor do they underpin an understanding of issues. But the idea that the Earth goes round the Sun (rather than vice versa) and rotates on its axis, and the way this can account for the seasons and for day and night, is surely something everyone should be helped to understand as part of their general education. It is part of coming to understand who we are and the sort of universe we inhabit. So too, in a different way, is an understanding of genetics and inheritance, and of evolution. The claim of these models to be included in the curriculum is largely cultural - that these ideas are cultural products of significance and beauty, and that a knowledge and understanding of them is life-enhancing.

The criteria, then, for choosing which models to include in the school science curriculum are their cultural significance and their role in underpinning an understanding, in broad terms, of issues which may enter the public domain or of personal actions. The models I would nominate, in no particular order, are:

- the atomic/molecular model of matter (emphasizing the scientific understanding of chemical reactions as rearrangements of matter)
- models of the Earth-moon and Earth-Sun systems, of the solar system, and of the universe
- the source-radiation-receiver model of interactions at a distance (leading to a ray model of light and of vision)
- the field model of interactions at a distance (gravitation, magnetism, electric fields)
- the 'germ' theory of disease
- the gene model of inheritance
- Darwin's theory of evolution of species
- models of the evolution of the Earth's surface (rock formation, plate tectonics)

The first two of these should be used, in part, to develop ideas about size, scale and distance, from the very large to the very small. The 'germ' theory is also valuable in this regard, in introducing ideas about entities at a scale between the visible and the atomic/molecular. The last two in the list should be used, in part, to develop ideas about time scales.

Some other elaborations and applications are also important. It is, for instance, important to make explicit the application of the idea of a chemical reaction to biological processes so that students appreciate, for instance, that digestion of food provides building blocks for new tissue, or that plants make additional bulk by chemical reactions which use raw materials from the plant's environment. The cycling of some key chemicals (for example, of oxygen and carbon dioxide in the atmosphere) is also an important idea, which depends on a certain level of understanding of the atomic/molecular processes within closed (eco)systems.

If we are really to 'do less but do it better', then some long established content will inevitably have to go. Some notable omissions from the content sketched above are the Newtonian model of motion, the scientific models of energy and change (entropy), a lot of detailed chemistry, waves, the scientific understanding of electric circuits, though several of these might remain, with a more technological emphasis as discussed above.

Understanding the methods of science

A second aspect of understanding science involves knowing about the methods of scientific enquiry. A major difficulty, however, is that there is not universal agreement about what these methods are. Many of the ideas which have been (and still are) communicated, both implicitly and explicitly, by the science curriculum about the methods of science are naive, and counterproductive from a public understanding of science point of view. 'Process science' and the 1991 version of the National Curriculum Sc1 [15] are cases in point. The idea that the method of science is to begin with unprejudiced observations, to look for patterns in these, then to form hypotheses from which specific predictions can be made and tested experimentally is a caricature of the way scientists work; and, in the hands of learners, it does not lead to scientific knowledge or understanding. Children come to science, at age five, already able to observe, classify, hypothesize, predict, compare 'fairly', and so on, with high levels of skill in contexts where they see the purpose in doing so. There is no need to spend lesson time 'developing' these capabilities.

It is, of course, easier to criticise the teaching of science method than to make detailed and realistic proposals about how to improve it. One critical issue to resolve at the outset, I think, is whether we consider an understanding of science method valuable because it provides a generally useful method of enquiry which people should be encouraged to use more widely (a transferable skills argument), or because it is important for everyone to know something about the way scientific knowledge has been, and continues to be, obtained. The former is based on the utility argument, the latter on the democratic, social and cultural arguments. There is little evidence to support the former argument: not only can no one describe the scientific method in detail, but it is also far from clear that a scientific approach is useful or appropriate, in most situations of practical decision-making. There is no universal algorithm for 'finding out', or even for 'weighing up the pros and cons'. On the other hand, knowing (as opposed to merely assenting to) the scientific explanation of a phenomenon involves being able to give grounds for holding ideas and propositions to be true. So an understanding of science content necessarily involves knowing something about how these ideas came to be held, and about the warrants for accepting them as useful and valid.

If our aim in the science curriculum, then, is to develop students' understanding of the ways in which scientific knowledge is obtained, it is useful to separate out two distinct strands:

- One has to do with the collection of empirical data which can serve as evidence in making or supporting a case. This involves an understanding of some procedural concepts, such as accuracy, reliability, validity. It has to do with understanding the relationship between a measurement or observation, and the 'truth'. It also includes the very notion of a measurement itself (the idea of a standard unit and a method of counting), of modelling behaviour in terms of relationships between variables, and of logical reasoning in situations involving several variables. Many of these ideas apply generally to systematic enquiry, not only in the sciences, and centre around the notion of evidence and the quality (or persuasiveness) of evidence. The curriculum implications, perhaps, are that practical work needs to give greater emphasis to uncertainty and error. Estimations of accuracy, reliability (the need to repeat measurements) and validity (are you measuring what you think you are measuring?) need to become much more commonplace, from an early age. We should try to avoid any suggestion that there is an infallible method, or algorithm, for gaining the sort of knowledge which can convince other people. This need not involve tasks with a high level of conceptual demand: convincing others that insulator A really is better than insulator B, or that shoe soles X really do grip better than soles Y could, in principle, do the job. And the use of evidence for persuading may need an audience, real or specifically created in the classroom, if it is to succeed.
- A second separate strand has to do with the role of theory in science. It involves understanding that the purpose of science is to generate explanations of the physical world which account for observed phenomena, and may predict others, or suggest phenomena to look for or

create. The theories we put forward as explanations do not simply restate the data in different terms. They are conjectures, made on the basis of available evidence and data, but never completely entailed by that evidence. Theories do not emerge from the evidence; there is always an element of creative speculation. They do not report the data, but propose explanations of it. Theorizing involves imagination and guesswork and risks being wrong. Understanding this strand of science method involves recognizing theory as separate from data, and being able to relate theory and data appropriately - to say, for example, whether given data agrees or disagrees with a given theory (or with several) and to draw logical conclusions from this.

Understanding science as a social enterprise
Of the three aspects of an understanding of science, this is perhaps the hardest to relate to a curriculum specification. Many science educators (those associated with the STS movement [16], for example) agree that this third dimension is important, but it is often unclear what it is 'about science' that they want students to know. From a curriculum point of view, a key issue is to clarify what, exactly, this third dimension amounts to. What, precisely, do we want young people to understand about the social structure and relations of science?

I would pick out two key ideas (whilst acknowledging that there may be others):

- That scientific knowledge is the product of sustained social work. It is developed through a struggle to understand, make sense and communicate and share ideas. Ideas emerge from acting on the world, not just talking about it.
- That there are crucial differences between science in the laboratory and in the real-world. In the lab, situations are simplified, so that one entity in the situation can be isolated from the interference of others, and hence understood. Real-world situations, however, are invariably messy and complex. So there is always some uncertainty about how (or even whether) the laboratory findings apply; and about what weighting to give to different pieces of evidence. And, in most cases of dispute, forms of knowledge other than scientific knowledge, and including values, are relevant to the decision-making process.

A science curriculum for public understanding should aim to help students develop their awareness of both of these. As regards the first, the curriculum would provide opportunities for students to get to know more about real scientific work, by looking at some examples in detail. These should range from the routine scientific work of a hospital lab histologist or water board analyst, to the 'normal' science of much industrial and university research, to the mould-breaking revolutionary developments in science. This might be provided through readings or video, but also surely by visits to places where science is done. And students should also, I think, learn something of the processes by which new scientific knowledge is produced: the sharing of new ideas and results at conferences and through papers in journals, the processes of refereeing and peer-review, the replication and checking of unexpected findings.

If we are thinking of the curriculum from 5-16, then we need a model of progression in this area, to guide the choice of examples used. Students might, over the period, study a number of specific examples of scientific work in some depth, chosen to illustrate, progressively, scientific ways of working such as:

- systematic, careful data collection (for example), in environmental monitoring or weather forecasting;
- 'inductive' pattern seeking (as, for example, in some epidemiology, or public health work);
- checking an idea by testing it (or a prediction based on it);
- proposing a new view of an area (such as Lavoisier's discovery of oxygen, or Pasteur's work on disease, or the continental drift and plate tectonic hypotheses).

One of the key messages from this sort of work should be that there is no single way in which science works to obtain new knowledge, and no guarantee of success in solving a problem. Looking at the 5-16 curriculum as a whole, the aim should be gradually to develop ideas about the need for a base of reliable data, the role of imagination in generating explanations, the reception of novel ideas, the causes of disputes and their eventual resolution.

Alongside these ideas about the development of scientific understandings of the world, there should also be some case studies of disputed applications of science, with the principal aim of highlighting the range of considerations (scientific and non-scientific) involved in reaching any practical decision. Here there are also clear links with understanding scientific methods of enquiry - in particular, ideas about reliability of data and the difference between data and explanation. Students should have experience of some extended studies, perhaps one each school year, in which they work in groups on a practical issue requiring them, as a group, to make and defend a decision with practical consequences. This sort of work would have to be supported by an extensive pack of background information and data.

SOME CONCLUSIONS

In the introduction to this article, I outlined some areas of concern about the current science curriculum: the evidence that little is learned, the sense that what is on offer may miss students' interests and needs, the dulling uniformity of pace. How would the curriculum for public understanding sketched above address these concerns?

First, I think, by identifying clearly a small number of key models as the core content to be taught, and by providing a framework which enables clear goals to be set for a developing understanding of scientific methods and of science as a social enterprise, it provides a better basis for improving understanding of key ideas and for monitoring the extent of understanding. For many of the key models, there is a considerable body of research data on children's ideas, learning difficulties and strategies for addressing these. Where there is not, clarity about aims would help us identify priority areas for further research and development of approaches.

Second, I think that a more technological emphasis, together with a focus on a small number of key models, would stand a better chance, if imaginatively presented, of catching and holding the interest of more students, than a curriculum whose structure and rationale is often unclear to teachers and must appear even less clear to learners.

Third, I would suggest that case studies, of the historical development of ideas, of actual scientific work (either contemporary or historical), of disputes about the application of science, and more extended practical investigations with a focus on assembling persuasive evidence to support a conclusion. These also provide appropriate contexts for students to voice their own views and opinions, and to defend these, as well as a means of varying the pace of science lessons - with groups of lessons devoted to more intensive development of key ideas, followed by others in which students undertake work which makes use of their developing understanding of these ideas, and so consolidates and reinforces it.

The science curriculum outline proposed above is no more than an outline sketch. It is not worked through in any detail. Issues of sequence and timing have not even been considered. Others may identify, and wish to argue for, different priorities. I hope that this article might stimulate debate. Hard questions need to be asked, and conventional answers challenged, if we are to move towards a science curriculum which is more suited to the task required of it, as a core element of the curriculum for all young people.

First we need to decide *why* we want to teach science to all our young people; from that we can perhaps work out *what* we want to teach them. Then research, linked closely to the development and evaluation of teaching materials and approaches, may be able to help us discover *how* best to teach these ideas. That, I think, is the project on which the science education community now needs to embark as a matter of some urgency. If this article contributes to opening up this agenda, then it will have served its purpose.

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It must be true – it was in a magazine

Pigs kill trees

Ammonia from animal wastes in intensive pig-rearing units is acidifying soils and streams, the National Environmental Research Council has found.

...

It (ammonia) reacts with nitrogen to cause nitrogen saturation, cited as a cause of tree dieback from acidification of the soil.

— *Country Life, 14 July 1994*