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What “Ideas-about-Science” Should Be Taught in School Science? A Delphi Study of the Expert Community

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Abstract: Recent arguments in science education have proposed that school science should pay more attention to teaching the nature of science and its social practices. However, unlike the content of science, for which there is well-established consensus, there would appear to be much less unanimity within the academic community about which “ideas-about-science” are essential elements that should be included in the contemporary school science curriculum. Hence, this study sought to determine empirically the extent of any consensus using a three stage Delphi questionnaire with 23 participants drawn from the communities of leading and acknowledged international experts of science educators; scientists; historians, philosophers, and sociologists of science; experts engaged in work to improve the public understanding of science; and expert science teachers. The outcome of the research was a set of nine themes encapsulating key ideas about the nature of science for which there was consensus and which were considered to be an essential component of school science curriculum. Together with extensive comments provided by the participants, these data give some measure of the existing level of agreement in the community engaged in science education and science communication about the salient features of a vulgarized account of the nature of science. Although some of the themes are already a feature of existing school science curricula, many others are not. The findings of this research, therefore, challenge (a) whether the picture of science represented in the school science curriculum is sufficiently comprehensive, and (b) whether there balance in the curriculum between teaching about the content of science and the nature of science is appropriate. © 2003 Wiley Periodicals, Inc. J Res Sci Teach 40: 692–720, 2003

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This article presents the findings of an empirical study conducted using a Delphi technique to answer the question, ‘‘What should be taught to school students about the nature of science?’’ The study was part of 1 of 4 projects of a network of research conducted by the University of York, the University of Leeds, the University of Southampton, and King’s College London, whose principal aim was to develop and improve evidence-based practice in science education. This project, funded by the UK Economic and Social Science Research Council under its Teaching and Learning Research Programme, sought to provide empirical evidence of what the expert community engaged in practicing, communicating, and teaching science thought was important for average citizens to understand about science (as opposed to a knowledge of its content) by the end of their formal education (currently age 16 in the United Kingdom).

The need for such a study was perceived to lie in the growing case for science education to provide a more effective preparation for citizenship (American Association for the Advancement of Science, 1993, 1998; Millar & Osborne, 1998). Although there has been almost global acceptance that formal science education should be an essential and compulsory component of every young person’s education, for example in the United Kingdom from the age of 5 to 16, there has been little attempt to develop a curriculum that is commensurate with such systemic reforms. Rather, science courses have been adapted from curricula whose roots lie in programs essentially conceived as foundational studies for those who were to become the next generation of scientists. Such syllabuses have assimilated elements of the nature of science through a piecemeal process of accretion. For instance, the latest version of the English National Curriculum (Department for Education and Employment, 1999) has acquired a component termed Ideas and Evidence that constitutes 5% of the mark of all national examinations. However, the core status of science can be justified only if it offers something of universal value to all rather than academic science for the minority who will become the next generation of scientists. Science courses that give scant or tacit treatment of the nature, practices, and processes of science result in most students leaving school with naive or severely limited conceptions of science (Driver, Leach, Millar, & Scott, 1996). Yet it is an understanding of the nature of science which many have argued is essential for the education of the future citizen (Fuller, 1997; Irwin, 1995; Jenkins, 1997; Millar, 1996; Ziman, 2000), and which should be an integral and substantive element of any contemporary course in science.

In most societies, the normative view of what is significant and salient within a given domain is defined by the academic community. However, contemporary academic scholarship would suggest that the nature of science is a contested domain (Alters, 1997; Labinger & Collins, 2001; Laudan, 1990; Taylor, 1996) with little agreement about any view that might be communicated in school science. Consequently, as Stanley and Brickhouse (2001, p. 47) pointed out, ‘‘although almost everyone agrees that we ought to teach students about the nature of science, there is considerable disagreement on what version of the nature of science ought to be taught.’’ Somewhat paradoxically, then, despite this obstacle, a range of curriculum documents such as *Benchmarks for Scientific Literacy* and others from New Zealand, Canada, the United Kingdom, and Australia (McComas & Olson, 1998) ostensibly seem to have achieved some agreement in defining what should be taught about the nature of science. But do these curriculum documents represent a consensus or, alternatively, the kind of compromise which is often the product of reports produced by committees? That is, do they represent the lowest common denominator around which it is possible to achieve agreement rather than any coherent account of the nature of science?

In the view of this uncertainty and the lack of empirical evidence for consensus, our essential research aim was to determine empirically the extent of agreement among scientists, science communicators, philosophers and sociologists of science, and science educators about those aspects of the nature of science that should be an essential feature of the school science curriculum:

in essence, to make a contribution toward resolving this apparent dichotomy between the academic and educational community.

The first section of this article therefore considers and reviews the nature of the debates and argument that surrounds those aspects of the nature of science that should or should not form part of the secondary school science curriculum; the second, major section presents the methodology and findings of the study; and the third, final section discusses the conclusions that can be drawn from this work and their implications for the teaching of science.

Teaching the Nature of Science

Why Teach the Nature of Science?

Science education attempts to wrestle with three conflicting requirements: what Collins (2000) termed the horns of a ‘‘trilemma.’’ 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 and create new knowledge and the emancipation that science offers from the shackles of received wisdom. Such attempts can be seen in the arguments of the advocates of the Nuffield course of the 1960s, where school science was to offer the opportunity to be a scientist for a day, with its implicit promise that this experience would offer a window into the intellectual engagement that science offers. More recently, it is embodied in the aspirations of the American educational reforms that students at all grade levels ‘‘should have the opportunity to use scientific inquiry and develop the ability to think and act in the ways associated with [scientific] inquiry’’ (National Academy of Science, 1995).

Yet, ironically, as Kuhn’s (1962) seminal analysis of the culture of science pointed out, science’s mechanism for achieving its aims is to rely, in contrast, on a dogmatic and authoritarian education in which students must accept what they are told as ‘‘unequivocal, uncontested and unquestioned’’ (Claxton, 1991)—the contrasting feature that forms the second horn of Collins’s trilemma. Such an education obscures or ignores any exploration of the nature of science, and consequently, only when students finally begin practicing as scientists do the workings of science become more transparent. Even then, the normative values and beliefs that dominate their practice can still remain unquestioned (Gaon & Norris, 2001). More important, however, such a science education ignores or neglects the third horn of Collins’s trilemma: the requirement to provide its students with some picture of the inner workings of science—knowledge, that is, of science-in-the-making (Latour, 1985)—and knowledge, moreover, which is essential for the future citizen who must make judgments of reports about new scientific discoveries and applications. For those who abandon the study of science at lower levels, evidence suggests that the failure to teach explicitly what constitutes the nature of science leaves many with simplistic or naive ideas about science (Driver et al., 1996). Yet, in a society where science increasingly permeates the daily discourse, some understanding of its underlying epistemic values, methods, and institutional practices is essential if the citizen is to engage with the issues confronting contemporary society.

Consequently, it could be argued that in a nontrivial sense, science education is science’s own worst enemy, leaving far too many students with a confused sense of the significance of what they have learned, an ambivalent or negative attitude to the subject itself—a product of its authoritative and nondiscursive mode of education (Osborne & Collins, 2000; Osborne, Driver, & Simon, 1996)—and insufficient intellectual tools to evaluate the claims of science and scientists critically. Remediating this weakness requires a reconsideration of the aims and purposes of science education and a determination of which ideas-about-science it might be important for the future citizen to know. That in turn requires some level of agreement (if not complete agreement) about some form of canonical version of the processes and practices of science and which elements are essential components of any school curriculum.

The Contested Nature of Science?

The one feature that emerges from an examination of the scholarship in the field of history and philosophy of science is that, if its intent was to establish a consensual understanding of the foundations of the practice of science, it might best be characterized as a failed project (Taylor, 1996). Notably, for instance, Laudan, Donovan, Laudan, Barker, Brown, Leplin, et al. (1986, p. 142) were forced to conclude that ‘‘the fact of the matter is that we have no well-confirmed general picture of how science works, no theory of science worthy of general assent.’’

More recently, Ziman (2000), too, commented that the philosophers of science ‘‘in spite of their heroic efforts have simply failed to come up with a satisfactory definition of ‘science.’’’ Even the informed lay observer would have noted that the past decade was characterized by a vigorous debate about the nature of science that was termed ‘the science wars.’ Put simply, authors such as Gross and Levitt (1994) and Sokal and Bricomont (1998) reacted strongly to the suggestion that much of scientific knowledge is a social construction. The case made against science has been one where Popperian notions of an objective reality and the truth-seeking goal of science have been replaced instead by the idea that the best that science can achieve are socially determined theories that are internally coherent and instrumentally viable but bear no necessary relation to any ontological reality.[1] Within education the best known proponent of such a view is von Glaserfeld (1995). Within philosophy, the case has been made that social practices and cultural influences shape not only the content and form of what is accepted as science (Collins & Pinch, 1993; Latour & Woolgar, 1986; Longino, 1990), but also its language (Gregory, 1988; Gross, 1996; Montgomery, 1996), to argue that science is a culturally located and gendered product (Haraway, 1989; Harding, 1991). Such views are encapsulated in the view articulated by Latour and Woolgar (1986) in their seminal study of scientists at work that:

> science is a form of fiction or discourse like any other, one effect of which is the ‘‘truth effect,’’ which (like all literary effects) arises from textual characteristics, such as the tense of verbs, the structure of enunciation, modalities and so on. (p. 184)

Other notable attacks on the values that underpin scientific practice were mounted by Collins and Pinch (1993), who argued that the notion of replicability is an impossible ideal as all experimental work is subject to the ‘‘experimenter’s regress’’—in essence, that because all experimentation depends on skill and experience, it can never be sure whether the second experiment was a test of the experimental results or a test of the ability of the experimenter, thus logically requiring further experiment, ad infinitum.

The response to such critiques has been virulent and acerbic, culminating in the now infamous hoax perpetrated on the editors of *Social Text* by Sokal (1996)—an affair that made even the pages of *The New York Times* (Fish, 1996). A more considered philosophical response came from Searle (1995). His basic argument is that we do not construct reality, but instead representations of reality. Any socially constructed representation of *X* must, however, be assembled out of elements *Y*, each of which in turn is constructed out of elements *Z*, and so on, and that this process must bottom out at some point in elements that are not institutional constructions. To take a trivial example, although money is a social construction, the gold or paper used to represent it is not. Likewise, within the science education community, similar debates have taken place between the proponents of a radical social constructivist view of learning (Tobin & Tippins, 1993; von Glaserfeld, 1995) and their critics (Matthews, 1995; Osborne, 1996; Phillips, 1995). Within the context of such a high-profile and public debate, therefore, it is hard to argue that there is an established consensus about the nature of science, let alone agreement about a version that might be communicated to students.

Indeed, empirical evidence for a lack of consensus comes from the work of Alters (1997), who surveyed the views of 210 members of the U.S. Philosophy of Science Association. Alters concluded from the 187 responses to his questionnaire that a "minimum of 11 fundamental philosophy of science positions are held by philosophers of science today" and therefore, that "there is no one agreed-on philosophical position underpinning the existing NOS in science education." Alters's interpretation of his results was that the only legitimate position for the science education community was to acknowledge that no singular account exists and adopt a pluralistic approach to teaching about the nature of science. However, the assumptions and methodologic base of Alters's work have been strongly contested (Smith, Lederman, Bell, McComas, & Clough, 1997). These authors critiqued Alters's work, arguing that he had selected the statements for his instrument on the basis that they were those for which there was the least consensus, and that many had problematic wording. Even then, Alters's data showed that 75% or more of those surveyed agreed with 6 or more of the statements (though not necessarily the same 75%). Furthermore, they argued, to base the work solely on philosophers was also problematic: Where were the voices of other interested and knowledgeable parties such as sociologists and historians of science and scientists themselves? Philosophers, after all, have a normative disciplinary inclination to disagreement and they concluded that better instruments were needed that avoided the limitations of this study. However, given the bitter disputes between scientists and the sociologists of science, it is not self-evident that incorporating a wider range of communities in his study would have led to greater consensus. Indeed, as Shapin (2001) pointed out, an examination of the many statements made about science by scientists alone exposes a remarkable disparity of view.

In contrast, we strongly suspect that if a group of, say, 50 physics professors were asked to complete the Hestenes Force Concept Inventory (1992), we would predict that they would achieve a level of agreement in excess of 90%, and that where there was significant disagreement, most of it could be accounted for by misinterpretations of the questions. In contrast, would a group of philosophers, sociologists, historians, science teachers, and scientists achieve anywhere near the same level of agreement if it were asked to complete one of the many instruments [for instance, those produced by the Scientific Literacy Research Center (1967), Welch and Pella (1967–1968), and Cotham (1979)] that exist to elicit knowledge and understanding of the nature of science? The one study that has attempted to compare the views of scientists and science teachers found that whereas there was no difference between scientists and science teachers, there was a significant difference between scientists and philosophy majors—the latter having a better understanding of the methodological aspects of science (Kimball, 1967–1968). Although we recognize the point made by critics such as Lederman, Wade, and Bell (1998) that such instruments are often flawed because they reflect the views and unavoidable biases of the developers, our point is that the failure, and possibly the impossibility of designing any objective instrument, is another factor which casts doubt on the extent to which consensus about the nature of science really exists.[2]

However, perhaps Smith et al.'s strongest argument against Alters's argument was that documents such as *Science for All Americans* (American Association for the Advancement of Science, 1989), *Benchmarks for Scientific Literacy* (American Association for the Advancement of Science, 1993), and the *National Science Standards* (National Academy of Science, 1995) all presented a cogent and consensual case for elements of the nature of science. All of these documents were the product of discussions that involved scientists, science educators, policy makers, science teachers, and others. Their production would suggest, therefore, that an accord permeates the community. Moreover, an analysis of eight curriculum standards documents (McComas & Olson, 1998) such as the *Benchmarks for Scientific Literacy*, *National Science Standards*, the *California State Standards*, and *National Curricula* in Australia, New Zealand, Canada, and England and Wales has shown that many of the elements in one document also exist in other national documents (see Table 4), which suggests that not only does a national consensus exist within the United States, but there is also international consensus about the elements of the nature of science that should be taught at the school level.

How then, the disinterested observer might ask, is it possible for the contributors to these documents to achieve such agreement when there is no consensus within the scholarly community? One answer is that, whereas some or all of these elements within national curricula might be contentious within the philosophical community, the consensus achieved in these documents represents a partial or simplified view of the nature of science. Science education has, after all, commonly relied on vulgarized or simplified accounts of science content as pedagogic heuristics for communicating a basic scientific understanding. For instance, the Bohr model of the atom is still a common feature of many textbooks and the discourse of science classrooms. Yet the use of this simplified, and now superceded, model of the atom passes unremarked upon by the academic community. Hence, if we are to ask science teachers to teach explicit aspects of the nature of science, it would seem both reasonable and timely that, as a community, we come to some agreement about what those aspects of a vulgarized account of science might be (Duschl, Hamilton, & Grandy, 1990), recognizing that although any account may be partial or even in some respects naive, it is better than no treatment at all. Moreover, like the Bohr model, such a simplified account of the nature of science might serve as a foundation for the development of more sophisticated understandings in later life.

For these reasons, we sought to conduct a limited, small-scale study to establish empirically whether there was a measure of consensual agreement within the expert community for an account of the nature of science, albeit reduced, contestable, and simplified, that might be offered to school students. In approaching this task we sought to counter some of the criticisms made by Smith et al. (1997) of Alters's study—in particular, that the study drew on only members of the Philosophy of Science Association. Ours, in contrast, sought to represent the views of a wider community of scholars than solely philosophers drawing from historian and sociologists of science, scientists, science educators, science teachers, science communicators, and philosophers. Moreover, all were recognized at least nationally and many internationally for their expertise and competence. Finally, the use of an open-ended questionnaire in which the effects of our views and ideas were minimized reduced the potential criticism that the data obtained were constrained by the nature of the instrument we used.

Methodology

The method chosen for eliciting the expert community's view was a three-stage Delphi study (Murray & Hammons, 1995) similar to those used in other curriculum-based explorations (Doyle, 1993; Häussler, Frey, Hoffman, Rost, & Spada, 1980; Smith & Simpson, 1995). The Delphi method aims to improve group decision making by seeking opinions without face-to-face interaction and is commonly defined as "a method of systematic solicitation and collection of judgements on a particular topic through a set of carefully designed sequential questionnaires, interspersed with summarised information and feedback of opinions derived from earlier responses" (Delbecq, Van de Ven, & Gustafson, 1975). Three features characterize the Delphi method and distinguish it from other group interrogative methods: anonymous group interaction and responses, multiple iteration of group responses with interspersed feedback, and the presentation of statistical analysis (Cochran, 1983; Cyphert & Gant, 1971; Dailey & Holmberg, 1990; Uhl, 1983; Whitman, 1990).

The Delphi technique has four principal advantages thought to be important in gaining the considered opinions of experts:

- It uses group decision-making techniques, involving experts in the field, which have greater validity than those made by an individual (Brooks, 1979).
- The anonymity of participants and the use of questionnaires avoid the problems commonly associated with group interviews: for example, specious persuasion or ‘‘deference to authority, impact of oral facility, reluctance to modify publicised opinions and bandwagon effects’’ (Martorella, 1991).
- Consensus reached by the group reflects reasoned opinions because the Delphi process forces group members to consider logically the problem under study and to provide written responses (Murray & Hammons, 1995).
- Opinions using the Delphi method can be received from a group of experts who may be geographically separated from one another (Murray & Hammons, 1995).

The main disadvantages of a Delphi study are seen as: the length of the process, researcher influence on the responses owing to particular question formulation, and difficulty in assessing and fully using the expertise of the group because they never meet (Murray & Hammons, 1995). The implementation of this Delphi study therefore attempted to take full account of the perceived advantages while recognizing the disadvantages. For example, as science educators, we (the researchers) have views on the teaching of the processes and practices of science. It was important that these views not impinge on participants’ responses. Therefore, little guidance was given as to the expected content of responses in the first round of the Delphi study. In the second and third rounds, care was taken to ensure, as far as possible, that participants’ own words were returned and that participants had ample opportunity to comment on any interpretation in our conflation of their responses.

The Delphi procedure seeks to establish the extent of consensus or stability in the community and typically ends after either consensus or stability of responses has been achieved. Brooks (1979) identified consensus as ‘‘a gathering of individual evaluations around a median response, with minimal divergence,’’ and stability or convergence is said to be reached when ‘‘it becomes apparent that little, if any, further shifting of positions will occur’’ (p. 378).

Commonly, the minimum number for a Delphi panel is considered to be 10 (Cochran, 1983) with reduction in error and improved reliability with increased group size. However, Delbecq et al. (1975) maintained that few new ideas are generated in a homogeneous group once the size exceeds 30 well-chosen participants. For this study, 25 experts[3] engaged in the study of science and its communication were recruited, although the final sample was 23 owing to attrition in Round 1. There was, however, no further attrition in the group across the next two rounds, reflecting the commitment of individuals to the process.

In this context, we chose to define *experts* as those with acknowledged expertise in communicating, using, or researching the processes and practices of science. The common element shared by the group was an interest in communicating ideas about science in their writing, teaching, or other work—all in essence having an experience of acting as ‘‘knowledge intermediaries’’ (Irwin, 1995) between science and its publics. Thus, we sought views from leading scientists ($n = 5$); historians, philosophers, and sociologists of science ($n = 5$); science educators ($n = 5$); and those engaged in the public understanding of science or science communication ($n = 5$). Criteria used in selecting experts included for scientist were Fellowship of the Royal Society, and for philosophers, sociologists, and science educators, books and publications of international repute. For science communicators it was a combination of publications of international repute or the holding of an eminent post within the field. Initially 20 people were approached by letter, and only 1 scientist and 1 science communicator declined. Two other individuals were recruited to replace them. In the case of teachers, the notion of expert is not commonly agreed upon. The major value of their views was a sense not only of what was important for children to learn, but also what might be pragmatically attainable. Therefore, we recruited 5 teachers who had achieved some public recognition for their work such as individuals who had won national awards for the quality of their teaching or were authors of science textbooks in widespread use in the United Kingdom. In the event, after the first round, 1 teacher and 1 science communicator dropped out, leaving a sample of 23 in total. As is standard in all such Delphi studies, none of the participants was aware of the identity the other participants.

Conduct of the Delphi Study and Analysis of Results

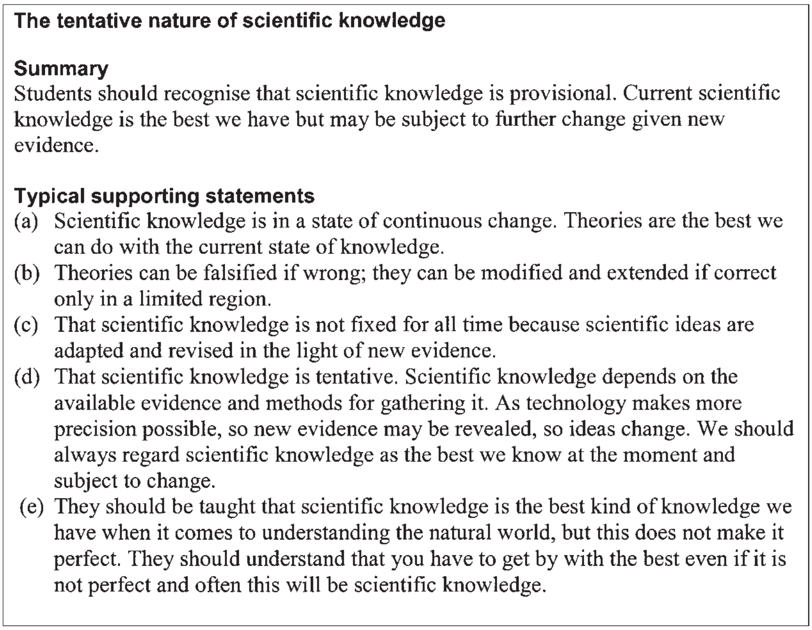
Round 1

The first stage of the study, begun in January 2000, was an open-ended brainstorming session. Opinions were sought about what essential ideas about science should be taught in the school science curriculum through the use of an open-ended questionnaire which asked: (a) What, if anything, do you think should be taught about the methods of science? (b) What, if anything, do you think should be taught about the nature of scientific knowledge? and (c) What, if anything, do you think should be taught about the institutions and social practices of science? For each response provided, participants were requested to give as clear a description of each idea as possible; to indicate a particular context where they thought a person might find the idea useful; and to state why such knowledge would be important for an individual to know.

This first round of the Delphi study elicited extensive comments from most participants. All these responses were coded reflexively and iteratively by two members of the research team using a computer-based qualitative data analysis package (NUDIST NVivo, QSR International Pty Ltd, Victoria, Australia) until a reliability of $>80\%$ was obtained. Thirty themes emerged from this analysis and a summary was composed for each emergent theme, capturing the essence of participants' statements. Discussion among four members of the research team resulted in agreed categorization of the responses and wording of theme summaries. Figure 1 shows a summary for one theme, The Tentative Nature of Scientific Knowledge, and some of the justifications provided by the participants. Early in the process, the decision was made to summarize the themes using language of an academic nature which was understood by the overwhelming majority of the participants. Such language has the advantage of offering economy and precision of meaning that was thought important for communicating ideas precisely with a minimum of misnterpretation. However, we recognize that, as currently articulated, the ideas embodied in the themes would have to be unpacked and elaborated for a practitioner audience. This process resulted in the production of 30 themes grouped under three major categories: The Nature of Scientific Knowledge,[4] the Institutions and Social Practices of Science, and the Methods of Science. Table 1 shows the titles of the themes grouped under these heading and the summary statements used in Round 3 to capture their meaning using key phrases articulated by the Delphi panel. It also shows the mean and modal ratings and the standard deviations in Rounds 2 and 3.

Round 2

The Round 2 questionnaire presented the titles and summaries of the 30 themes, together with representative anonymous comments obtained from individuals in Round 1, an example of which



The tentative nature of scientific knowledge

Summary

Students should recognise that scientific knowledge is provisional. Current scientific knowledge is the best we have but may be subject to further change given new evidence.

Typical supporting statements

(a) Scientific knowledge is in a state of continuous change. Theories are the best we can do with the current state of knowledge.
(b) Theories can be falsified if wrong; they can be modified and extended if correct only in a limited region.
(c) That scientific knowledge is not fixed for all time because scientific ideas are adapted and revised in the light of new evidence.
(d) That scientific knowledge is tentative. Scientific knowledge depends on the available evidence and methods for gathering it. As technology makes more precision possible, so new evidence may be revealed, so ideas change. We should always regard scientific knowledge as the best we know at the moment and subject to change.
(e) They should be taught that scientific knowledge is the best kind of knowledge we have when it comes to understanding the natural world, but this does not make it perfect. They should understand that you have to get by with the best even if it is not perfect and often this will be scientific knowledge.

Figure 1. Justification of one theme from Round 1 and its presentation for Round 2.

is shown in Figure 1. Participants were requested to rate the importance of each theme to the compulsory school science curriculum, as represented by the summary, on a 5-point Likert scale, with a score of 5 representing the highest degree of importance. In addition, they were then asked to justify their rating and comment on how accurately the title and wording of the theme reflected their understanding of a specific feature of science. Participants were also invited to comment and respond to the representative supporting statements.

Means, modes, and standard deviations for each theme using the rating given on the 5-point scale were calculated and are shown in Table 1. A total of 8 themes had a mean of ≥ 4, indicating at this early stage that they were viewed by the panel as very important or important. Of these 8 themes, 3 showed standard deviations of <1.0, indicating a high level of consensus for these themes: Experimental Methods and Critical Testing, The Tentative Nature of Scientific Knowledge, and the Historical Development of Scientific Knowledge.

Many comments were also made about the interrelated nature or similarities among many of the themes. The outcome was a decision to merge three pairs of themes, to split one theme and to modify the summary statements of most themes to minimize overlap. Figure 2 shows a revised version of the theme presented in Figure 1.

Round 3

For the third and final round, we decided to reduce the number of themes for consideration by the panel to only the most highly rated themes from Round 2. This action was taken because research literature on the Delphi method suggests that, in studies where participants were required to complete lengthy and detailed questionnaires, responses to questions toward the end of the questionnaire tend to be less fulsome and informative (Judd, 1971). Therefore, the research team was concerned that participant fatigue would result if the complete set of 28 ideas-about-science

Table 1

Themes for Round 2 of Delphi study, including ratings given in Round 2

Theme Title and Summary	ROUND 2			ROUND 3		
	Mean	Mode	*SD*	Mean	Mode	*SD*
Nature of Scientific Knowledge	4.3	5	0.96	4.2	4	0.93
Science and Certainty (Round 3)/Tentative Nature of Scientific Knowledge (Round 2)						
Students should appreciate why much scientific knowledge, particularly that taught in school science, is well-established and beyond reasonable doubt, and why other scientific knowledge is more open to legitimate doubt. It should be explained that current scientific knowledge is the best we have but may be subject to change in the future, given new evidence or new interpretations of old evidence						
Historical Development of Scientific Knowledge	4.0	4	0.95	4.3	5	0.94
Students should be taught some historical background to the development of scientific knowledge						
Cumulative and Revisionary Nature of Scientific Knowledge	3.9	4	1.04	3.7	5	1.27
Students should be taught that much scientific knowledge is cumulative, building on that which is already known. New theories and methods are often resisted but ultimately may be accepted if they are seen to have better explanatory power, parsimony, or elegance						
Empirical Base of Scientific Knowledge (Round 3)/Types of Knowledge (Round 2)	3.7	4	1.05	3.6	4	0.92
Students should be taught that there are different types of scientific knowledge, particularly the difference between representations in school texts and that at the frontiers of science research						
Status of Scientific Knowledge (Round 3)/Features of Scientific Knowledge (Round 2)	3.7	4	1.36	2.8	3	1.21
Students should be taught that scientific knowledge produces reliable knowledge of the physical world and has a number of attributes. Scientific knowledge aims to be general and universal, it can be reductionist and counterintuitive, and it has intrinsic cultural value. Scientific explanations are based on models and representations of reality						
Common Conceptions of Science and Risk	3.6	3	1.26			
Students need to be taught that common public perceptions of science perpetuate a number of myths which give erroneous impressions of the methods and nature of science. An understanding of the basic concepts associated with risk and uncertainty						
The Language of Science	3.3	3	1.05			
Students should be taught that science has a distinctive but common language. Scientific language evolves with use. Terminology needs to be used with care, with meanings clearly explained						

(*Continued*)

Table 1 (*Continued*)

Theme Title and Summary	ROUND 2			ROUND 3		
	Mean	Mode	*SD*	Mean	Mode	*SD*
Science as Human, Collaborative Activity						
Students should be taught that the production of scientific knowledge is a human activity undertaken both by individuals and groups. Any new knowledge produced is generally shared and subject to peer review. Although scientists may work as individuals they contribute to the communal generation of a common, reliable body of knowledge	3.3	4	0.98			
Reporting Scientific Findings	3.2	4	1.31			
Students should be taught that scientists use distinctive forms of communication for reporting results which are reliant on a range of different genres and semiotic modes						
Scientific Knowledge and Values	2.9	3	1.54			
Students should be taught that scientists perceive and claim their work to be value free and objective. This assumption is open to challenge						
Distinction between Science and Technology	2.3	3	1.36			
Students should be taught that there is a distinction between science and technology						
Methods of Science						
Scientific Methods and Critical Testing (Round 3)/Experimental Methods and Critical Testing (Round 2)	4.4	5	0.73	4.4	5	0.79
Students should be taught that science uses the experimental method to test ideas, and in particular, about certain basic techniques such as the use of controls. It should be made clear that the outcome of a single experiment is rarely sufficient to establish a knowledge claim						
Analysis and Interpretation of Data	4.1	5	1.27	4.2	5	0.88
Students should be taught that the practice of science involves skilful analysis and interpretation of data. Scientific knowledge claims do not emerge simply from the data but through a process of interpretation and theory building that can require sophisticated skills. It is possible for scientists legitimately to come to different interpretations of the same data, and therefore to disagree						
Hypothesis and Prediction	4.0	5	1.07	4.2	5	1.00
Students should be taught that scientists develop hypotheses and predictions about natural phenomena. This process is essential to the development of new knowledge claims						
Diversity of Scientific Thinking (Round 3)/Diversity of Scientific Method (Round 2)	4.0	4	1.07	4.2	4	0.71
Students should be taught that science uses a range of methods and approaches and that there is no one scientific method or approach						
Creativity	4.0	5	1.13	4.4	5	0.72
Students should appreciate that science is an activity that involves creativity and imagination as much as many other human activities, and that some scientific ideas are enormous intellectual achievements. Scientists, as much as any other profession, are passionate and involved humans whose work relies on inspiration and imagination						

Science and Questioning Students should be taught that an important aspect of the work of a scientist is the continual and cyclical process of asking questions and seeking answers, which then lead to new questions. This process leads to the emergence of new scientific theories and techniques which are then tested empirically	4.0	5	1.28	4.2	4	0.68
Observation and Measurement Students should be taught that observation and measurement are core activities of scientists; most measurements are subject to some uncertainty but there may be ways of increasing our confidence in a measurement	3.9	5	1.02	3.9	5	0.79
Specific Methods of Science Students should be taught a range of techniques for data representation and analysis commonly used in the sciences, with particular emphasis on those necessary for interpreting reports about science, particularly those in the media	3.9	4	1.08	3.8	4	1.07
Science and Technology Students should be taught that although there is a distinction between science and technology, the two are increasingly interdependent as new scientific discoveries are reliant on new technology and new science enables new technology	3.7	4	0.88	3.8	4	0.8
Cause and Correlation Students should be taught that there are two types of distinctive relationship in science: causal, in which there is a known mechanism relating an effect to a cause, and a correlation, in which identified variables are associated statistically but for which there is no well-established causal link	3.7	5	1.39	3.7	3	1.14
Role of ICT Students should be taught that Information and Communication Technology is now a fundamental tool which is inherent to the practice of science	2.8	2	1.51			
No General Ideas Independent of Science Content Students should be taught that there are no general ideas to be taught in science. Nothing can be taught about science independent of its content, and knowledge of the methods, institutions, and practices varies between sciences	2.2	1	1.51			
Institutions and Social Practices in Science						
Moral and Ethical Dimensions in Development of Scientific Knowledge Students should appreciate that choices about the application of scientific and technical knowledge are not value free; they may therefore conflict with moral and ethical values held by groups within society	3.9	5	1.33	4.0	5	1.00

(Continued)

Table 1 (*Continued*)

Theme Title and Summary	ROUND 2			ROUND 3		
	Mean	Mode	*SD*	Mean	Mode	*SD*
Cooperation and Collaboration in Development of Scientific Knowledge	3.6	5	1.47	4.2	5	0.79
Students should be taught that scientific work is a communal and competitive activity. Although individuals may make significant contributions, scientific work is often carried out in groups, frequently of a multidisciplinary and international nature. New knowledge claims are generally shared and, to be accepted by the community, must survive a process of critical peer review						
Developments in Scientific Knowledge are Subject to Peer Review	3.6	4	1.26			
Students should be taught that developments In scientific knowledge are critically reviewed and may be authenticated and validated by members of the wider community						
Contextual Nature of Science	3.3	3	1.22			
Students should know that developments in scientific knowledge are not undertaken in isolation, but may be shaped by particular contexts						
Constraints on Development of Scientific Knowledge	3.0	3	1.05			
Students should know that scientific knowledge is developed within the context of a range of constraints that may shape it and its uses						
Range of Fields in Which Scientific Knowledge Is Developed	2.7	4	1.24			
Students should be taught that scientific research is undertaken in a variety of institutions by individuals who have differing social status within the scientific community. Scientists generally have expertise only in one specific subdiscipline of science						
Accountability and Regulation of Scientific Practices	2.3	2	0.88			
Students should be taught issues of accountability and regulatory procedures that relate to the development of scientific knowledge						

Note. Themes are in the order resulting from Round 2.

Round 3

Science and Certainty

Summary

Students should appreciate why much scientific knowledge, particularly that taught in school science, is well-established and beyond reasonable doubt, and why other scientific knowledge is more open to legitimate doubt. It should also be explained that current scientific knowledge is the best we have but may be subject to change in the future, given new evidence or new interpretations of old evidence.

Typical comments in support

(a) It is not simply a matter of 'new evidence'. It is sometimes a matter of new perspectives. I would wish to stress this. Think not only of Galileo, Newton and Darwin, but of countless others (Fleming) in science and technology who have made progress by re-conceptualising a problem or even identifying the problem in the first place. I would want to find room for the incompleteness of scientific knowledge. The DNA structure is only part of the genetic code. We still do not know how proteins fold!

(b) Scientific knowledge is provisional not because it goes beyond the 'facts', but because the 'facts' will change and go beyond the science!

(c) Arguably the most essential of all, from the conceptual standpoint and public policy standpoint, provided it is linked well with Theme 1 (The Empirical Base of Scientific Knowledge) and Theme 2 (The Status of Scientific Knowledge and The Characteristics of Scientific Knowledge)

Figure 2. Nature of scientific knowledge: Revised version for Round 3 and participants' comments from Round 2.

were included in Round 3 of the study, affecting the level of detail in responses toward the end of the questionnaire. Thus, only the themes with a mean rating of >3.6 and/or mode of 5 were used for the third round, reducing the number of themes in this round to 18.

The final questionnaire of the Delphi study, distributed in May 2000, presented the titles, revised summaries, and representative anonymous supporting statements from participants for the top rated 18 themes from Round 2, together with the mean and standard deviation calculations of the ratings for each theme. Participants were requested to rate again each theme, based on the premise that it should be taught explicitly, to justify their rating, and to comment on ways in which the wording of the summary might be improved to reflect the essence of each idea-about-science. Mean scores and standard deviations were again calculated using the 1–5 response categories and are shown in Table 1.

Consensus and Stability

There is little guidance in the literature to inform decisions about the minimum level of agreement that might constitute consensus. Therefore, it was necessary for the research team to decide on an appropriate figure. For this Delphi study consensus was defined as a minimum of two-thirds, or 66%, rating a theme as ≥ 4 on the Likert scale. Stability was defined as a shift of one-third or less in participants' ratings between Round 2 and Round 3.

From analysis, 9 themes emerged for which there was both consensus and stability in being rated as important for inclusion in the science curriculum. These themes, highlighted in Table 1, were: Scientific Methods and Critical Testing, Creativity, Historical Development of Scientific Knowledge, Science and Questioning, Diversity of Scientific Thinking, Analysis and Interpretation of Data, Science and Certainty, Hypothesis and Prediction, and Cooperation and Collaboration. The last theme, however, was less stable than the others because an examination of individual participants' ratings across the two rounds, as opposed to the group's ratings, showed considerable instability in their ratings of this theme between Rounds 2 and 3. This finding may be a consequence of the revision of this theme from Round 2 to Round 3 because participants commented that the two themes, Science as a Human Collaborative Activity and Cooperation and Collaboration, were similar. Participants may have perceived the resultant merged theme as having undergone a more significant change than the others, leading to a significant difference in how it was rated.

Participants were urged to provide detailed comments in this round to justify and explain the rating given for each theme based on the premise that it should be explicitly taught. A summary of the justifications they offered for rating these aspects of the nature of science so highly follows.

Scientific Method and Critical Testing. The highest priority was assigned to this theme in both Rounds 2 and 3. Participants viewed the theme as the articulation of the ''core process on which the whole edifice of science is built'' (PU3).[5] The experimental method was said to be ''what defines science'' (S1), and was the ''central thrust of scientific research'' (SE2), and as such must be an essential part of the school science curriculum. One participant stated that students frequently formed the view that the purpose of practical work was to teach them techniques; ''they do not understand that in the research world of science, careful experimentation is used to test hypotheses'' (S5). The theme was seen to provide opportunities to develop what was already a major component of the English National Curriculum for science (PU1) and to highlight the importance of testing ideas as the basis of science (T2). The testing of ideas was an important issue for one participant who expressed the view that many science courses and texts labeled as experiments what were in reality demonstrations, and therefore not a test of scientific ideas (SE1).

Creativity. Although a number of participants thought that this theme was not easy to teach explicitly, it was nevertheless considered important that school science offer students opportunities to be genuinely creative ''and not just told how imaginative and clever scientists are/were'' (SE3). Students should be encouraged to ''do science, rather than being taught about creativity'' (PU3), and they should be encouraged to engage in activities such as creating models/pictures to explain ideas (SE3) and to consider possible ideas to explain phenomena and test hypotheses (PU5). To counter the image of science as a ''stodgy fact-filled subject'' (S3) and ''dispel the notion of scientists as nerds'' (S5), students should be encouraged to view science as ''fun and fascinating—and rewarding'' (S3) and to appreciate that ''creative science is a more exciting pursuit than most'' (S5). In emphasizing the importance of creativity in school science, one participant made the point that ''All too often students are turned off science by the large amount of rote learning involved. Indeed some students move to the arts/humanities because they find there a far greater potential to exercise their creativity. This is a crucially important message to communicate'' (PS05).

Historical Development of Scientific Knowledge. There was widespread agreement among the panel that this theme was capable of being taught explicitly and was an important component of students' learning in science. Teaching the history of science had the potential to facilitate an appreciation of developments in science, as well as the ways and extent to which such developments have been affected by the demands and expectations of society at different points in history (PS5).

The theme was seen as an antidote to rote learning because it emphasized science as a human activity; for example, "through it [history of science] even young students can come to understand personal aspects of scientific enquiry" (SE4). However, not only is it important in adding human interest to science lessons, it also fosters a realization of the ways in which ideas have been tested and developed in the past, and the ways in which this has informed continued developments in science (SE5). It was suggested that for students who lacked interest in science or experienced difficulties in learning aspects of science, adopting a historical perspective may be "a hook to catch their interest" (PS2).

Science and Questioning. Participants agreed that questioning was "part and parcel of the process of science" (SE1) because it reinforced the notion that "science is characterized by unfinished business" (PU1) and emphasized the importance of continual testing and evolution of understanding (S1). It was stressed that the explicit teaching of questioning should form an integral part of teaching in science—"the more pupils question, the more they understand the thinking behind the scientific knowledge" (T2). As the following comment shows, the value of engagement in the cyclic process of questioning and seeking answers was not limited to science, but has wider application in the curriculum.

> Questioning is the engine of human development and is not specific to science. While knowledge is obviously important, it is given far too central a place in our education system. Although it is much easier to grade students in terms of their knowledge, knowledge by itself is useless unless it leads to the forming of new and pressing questions and inculcates an attitude that applies to all areas. (PS5)

Diversity of Scientific Thinking. The importance of this theme lay in the potential to provide students with firsthand experience of the breadth of scientific activity (PU3). It was seen to "help nip scientism in the bud" (PU4), indicating to pupils that the world might be explored through a range of means. The theme offered opportunities to develop an understanding that "science is not rigid—a number of methods may be used to solve the same problem" (PU2). It encouraged teachers to "get away from the simplistic notions of how science is done" (SE2), to enable students to select the most appropriate method for the problem being addressed and "the degree of confidence required of the outcome" (SE2). Another benefit to students was a toolkit of scientific methods to test their ideas, together with a growing awareness that in some circumstances scientists need to develop new methods or adapt an old one to test a particular idea (SE3).

One participant, however, was keen to stress teaching common elements of scientific methods:

> Different disciplines have different methodologies and approaches, but all in the end rely upon observation, theorizing, experiments, testing, refinement of theory leading to acceptance or rejection of theory, so they have something in common. (S5)

Another wished to include in the theme mention of those aspects of science for which experiments were not appropriate or realistic; for example:

> Cosmology, most geology, most histology, most taxonomy are impossible to look at with experiment; in some medical research it is unethical to undertake possible experiments. (PU5)

Yet another suggested the substitution of the word *method* in the summary with *inquiry* or *investigation*. Nevertheless, the majority of participants expressed the view that the theme summary captured the essence of the intrinsic concepts. It was said, for example, to be ‘‘a good summary of a rather slippery point’’ (PS02).

Analysis and Interpretation of Data. There was particular emphasis in participants' justifications on the second part of the summary statement. It was said, for example, that ‘‘it is crucial to know that scientific data does not stand by itself, but can be variously interpreted’’ (PS1) and that students need to be taught that data do not ‘‘speak by themselves—instead they require other layers of interpretation’’ (PS5). An understanding that scientists may legitimately come to different interpretations of the same data was thought to be an important concept for all students, ‘‘not only those individuals who might later pursue a science-related career, but also for those students who do not’’ (PS5). Three participants expressed the view that analysis and interpretation of data would be taught more effectively if students were encouraged to generate and use their own data (SE3). This view was supported and developed by another member of the panel with the following justification:

> . . . It is important that students do their own research—then, just like practicing scientists, they will be interested in the analysis and interpretation of data. Such explorations by a number of groups in the same class could well lead to different interpretations. The conflicting claims of opposing pressure groups could be used to highlight the data in different ways. It is important for students to be more critical of science and to question the results—this theme encourages a more objective view of science and scientists. (PU06)

Science and Certainty. Members of the panel agreed that the provisional nature of science implicit in this theme was an ‘‘extremely important concept’’ (S5) in school science. It was important for students to appreciate that when there appear to be right answers in school science, this is because ‘‘questions are asked which are capable of quantitative determination’’ (S5). In contrast to this, questions asked by scientists working in the field frequently could not be answered at present, either because the questions were too complicated to be amenable to sensible experimentation or simply because experiments have yet to be undertaken—for example, Genetically Modified (GM) foods, Bovine Spongeiform Enchopolopathy (BSE) (S5).

The theme had the advantage of highlighting the contemporary nature of science, suggesting that there was more to be discovered—a concept considered important in encouraging students to consider a career in science (PU2). However, two participants expressed concern that in overemphasizing the tentative nature of much scientific knowledge, students might be led to feel that science is ‘‘about something, but they do not know what’’ (T1). It was also said that for the vast majority of people, such an emphasis was not relevant. It was thought, for instance, to be more important for teachers to explain that ‘‘there are certain areas where we remain largely ignorant, e.g., how the brain works’’ (S3).

One participant expressed reservations about the explicit teaching of the theme, their point being that students would require specialist knowledge of science to understand areas of current uncertainty in science and there was a danger that ‘‘this may push teachers toward transmission of facts’’ (SE3).

There was some disagreement among members of the panel about the wording of the summary. As the comment below shows, one participant felt that the theme summary conveyed a message that was ‘‘somewhat sophisticated’’ and might be difficult to absorb into the current school science curriculum:

> At one level it requires the child *not* to question school science; at another to view ‘‘frontier’’ science as *not* beyond question. Where does the boundary lie between those two types of science? (PS5).

Hypothesis and Prediction. This theme was described as ‘‘essential’’ (SE1) for students to understand that making predictions and collecting evidence to test them is central to testing hypotheses and developing explanations (SE5). Others argued that it was ‘‘the very basis of science’’ (S3). Formulating hypotheses and testing predictions were said to be ‘‘the spark that ignites any scientific activity’’ (PU2) and was as relevant for students in science lessons as it was for the scientist in the laboratory.

A number of participants linked hypotheses and predictions and creativity in science. As such, the theme was described as an antidote to ‘‘just fact collecting’’ (S3) and showed that science was concerned more with ‘‘testable theory’’ than with ‘‘fact’’ (PU4, T1, S2). One participant stressed the value of this theme to the broader context of students’ education by stating that:

> This has many applications outside science—it is a good prescription for thinking critically about almost any topic. Thus it encourages an attitude that should be of help, not only to science students, but also those with no intention of pursuing science. (PS5)

To ensure the effective teaching of this theme, one participant thought it advisable to clarify the meaning of the term *scientific hypothesis* used in the theme summary, as there was good research evidence to show that ‘‘students have difficulty in being clear what is meant by the term’’ (SE2).

Cooperation and Collaboration in the Development of Scientific Knowledge. This theme was seen as offering students a useful perspective on scientific activity, said to be ‘‘too often viewed as the retreat of the lone genius’’ (PS5). It was considered important that teaching the theme stress the social processes in science, as this was an aspect too often overlooked in school science (PS5). The inclusion of the peer review process in this theme was thought important because it showed that scientists ‘‘go one step further in being reviewed by their peers, so adding to the validity of new scientific knowledge’’ (PU2). The theme was said to be ‘‘fundamental to understanding both the contingency and the reliability of knowledge’’ (PU4) and, in evaluating new knowledge claims, it was important that students gained an understanding of the variety of communities in which scientific knowledge is developed (PU1). Participants generally felt that the explicit teaching of the theme was relatively straightforward, best achieved through encouraging students to engage in collaborative work in science lessons and possibly to engage in peer review of each other’s work. However, one participant was concerned that an emphasis on collaboration in school science should not obscure the social process of ‘‘criticism, disagreement, and competition’’ (PS2).

Variance in Group Ratings

We conducted an analysis of the degree of variance of data in ratings of subgroups of the Delphi panel (Table 2). The subgroups were research scientists (S), philosophers and sociologists of science (PS), science educators (SE), those involved in the enhancement of public understanding of science (PU), and science teachers (T). This analysis was conducted to see (a) what the variance was within the groups, and (b) whether there were significant differences between the mean ratings of the groups: that is, did the ratings—for instance, of the scientists—differ significantly from those of, for instance, the philosophers and sociologists?

Table 2

Analysis of variance of participants' responses for Round 3 of Delphi study Analysis of variance for Round 3 themes

Theme Title	Variance for Round 3					Mean Group Responses					
	S	PS	SE	PU	T	S	PS	SE	PU	T	Mean
Science and Certainty	0.6	0.3	0.3	0.3	2.2	3.8	4.5	4.4	4.5	3.8	4.0
Experimental Methods and Critical Testing	0.1	0.6	0.8	1.0	1.3	4.8	4.1	4.4	4.5	4.0	4.4
Analysis and Interpretation of Data	0.6	1.5	1.0	0.9	1.0	4.2	4.1	4.0	4.0	4.5	4.2
Specific Methods of Science	0	0.3	1.1	1.6	3.7	3.9	4.0	4.0	2.8	3.9	3.7
Diversity of Scientific Method	0.1	1.3	0.2	0.2	0.3	3.9	3.7	4.2	4.7	4.8	4.2
Historical Development of Scientific Knowledge	0.3	0.5	2.5	0.3	0.8	4.6	4.5	3.5	4.3	4.2	4.2
Moral and Ethical Dimensions in Development of Scientific Knowledge	0.4	0.6	0.8	0.9	2.7	3.0	4.1	4.4	4.5	4.2	4.0
Science and Questioning	0.6	0.8	0.3	0.5	0.3	4.1	4.1	4.1	4.0	4.8	4.2
Cumulative and Revisionary Nature of Scientific Knowledge	1.4	1.3	1.8	0.3	3.4	4.0	2.6	3.6	4.5	3.7	3.7
Creativity	0.2	0.7	0.7	0.7	0	4.7	3.9	4.2	4.0	5.0	4.4
Hypothesis and Prediction	0.1	0.9	0.8	0.2	3.6	4.8	3.4	4.4	4.4	3.8	4.2
Cooperation and Collaboration in Development of Scientific Knowledge	1.0	0.8	0.6	0.7	1.0	4.0	3.9	4.2	4.5	4.5	4.2
Observation and Measurement	0.7	0.5	0.6	0.7	0.9	4.2	3.4	3.8	4.1	4.4	4.0
Science and Technology	0.4	0	0.7	1.3	0.3	4.0	4.0	3.8	3.0	4.5	3.9
Status of Scientific Knowledge	1.2	1.3	1	3.3	1.0	3.3	2.3	3.0	3.0	2.0	2.8
Characteristics of Scientific Knowledge	0.7	1.3	1.5	0.4	0.3	3.7	3.5	3.5	4.3	3.8	3.7
Cause and Correlation	0.4	2.1	1.0	0.8	3.6	3.6	3.2	4.0	4.2	3.8	3.7
Empirical Base of Scientific Knowledge	1.3	0.7	0	0.8	2.0	3.8	3.3	4.0	3.7	3.0	3.6

Variance within Groups

The analysis showed that Round 2 data showed large variance (>1.5 points on the Likert scale) in the subgroups of scientists (S) and philosophers and sociologists of science (PS) for 5 and 9 themes, respectively. In Round 3, however, variance within these two subgroups decreased, showing no themes in which any large variance was evident in subgroup scientists (S) and only one theme with variance >1.5 for the subgroup of those engaged in the public understanding of science (PS) (Table 2).

The greatest increase in variance between Rounds 2 and 3 was for the subgroup of teachers of science. For this group there were 7 themes in which the variance was >1.5, an increase of 5 themes from the previous round. Themes for which the variance was >3 for this subgroup included the themes Cause and Correlation, Cumulative and Revisionary Nature of Scientific Knowledge, Specific Methods of Science, and Hypothesis and Prediction.

In part, the large variance in the teachers' group can be explained by the smaller group size of 4 individuals as opposed to 5. However, the group PS was also this size and their variance was not as large. With a sample of this size it is difficult to draw general conclusions, but the results suggest a lack of consensus among science teachers themselves about what should form the principal constituents of any account of the nature of science—an aspect which needs further research.

Variance between Groups

Differences between mean ratings of each subgroup were explored using analysis of variance for each of the 18 themes as the dependent variable against the groups as the independent variable. Table 3 shows the result of this analysis: No significant difference was found. Only one of these tests approached significance but this was not sustained by a Scheffé posthoc test.

With such small group sizes, significant differences will be found only when the range around any one mean is both small and widely separated from another group. That the results do not approach significance suggests an absence of difference between groups and indicates unanimity or accord across all subgroups.

Related and Similar Themes

Although the themes have been presented as discrete entities, it was evident from the comments of the participants that many perceived distinct interrelations between themes. To express this interrelation, we scrutinized all participants' comments on Round 3 statements for expressions of links and maps constructed of their interrelations, full details of which can be found in Osborne et al. (2001). The resulting map showed the nature and frequency of identified links between Round 3 themes.

This map illustrates the clear links participants had identified between major themes, indicating an expectation that although the themes should be taught explicitly, they would not be addressed in isolation. It is notable that the nine highly rated themes all have links with each other and multiple links with other themes—supporting the view that these are not to be seen as independent entities but interrelated aspects. In contrast, Science and Technology, and Moral and Ethical Dimensions in the Nature of Scientific Knowledge are seen as discrete entities, implying that these themes were seen as qualitatively different from the interrelated strands at the heart of the nature of science.

Table 3
Results for ANOVA test conducted for each theme against subgroup composition

	Theme Title	Degrees of Freedom	*F*	*P*
8	Science and Certainty	4	0.65	.63
23	Scientific Methods and Critical Testing	4	0.69	.61
18	Analysis and Interpretation of Data	4	0.17	.95
19	Specific Methods of Science	4	0.73	.58
22	Diversity of Scientific Method	4		
4	Historical Development of Scientific Knowledge	4	1.13	.36
16	Moral and Ethical Dimensions in Development of Scientific Knowledge	4	2.17	.11
27	Science and Questioning	4	0.75	.56
9	Cumulative and Revisionary Nature of Scientific Knowledge	4	1.55	.22
21	Creativity	4	2.29	.09
24	Hypothesis and Prediction	4	1.42	.26
15	Cooperation and Collaboration in Development of Scientific Knowledge	4	0.36	.83
25	Observation and Measurement	4	1.35	.28
28	Science and Technology	4	2.81	.055
2A	Status of Scientific Knowledge	4	0.90	.48
2B	Characteristics of Scientific Knowledge	4	0.17	.95
20	Cause and Correlation	4	0.24	.91
1	Empirical Base of Scientific Knowledge	4	1.05	.41

Conclusions

So far, where individuals have thought extensively about the nature of science, and about an account that should be offered to others, they have experienced considerable difficulty in its specification—some of which is apparent in the data collected for this study. There has been little agreement about what is core or absolutely essential to an understanding of science. As Ziman (2000, p. 8) argued, "Just when society ought to be getting sympathetic well-informed advice from their metascientific colleagues, they are being offered little but deconstruction and doubt."

In contrast, our findings provide empirical evidence of a consensus on salient features which are both significant and essential components of any basic knowledge and understanding about science and, in addition, uncontroversial within the relevant academic communities with an interest in science and science education. These data suggest, then, that these themes do have sufficient agreement to form the core of a simplified account of the nature of science suitable for the school science curriculum. Hence, our first conclusion is that there exists support and broad agreement for a set of nine clearly specified themes about aspects of the nature of science which school students should encounter by the end of compulsory schooling. The evidence for this conclusion lies in the high degree of consensus and stability surrounding these themes (Table 1) and in the low variation in these ratings both within and between groups (Tables 2 and 3).

A concern arising from this study is that the findings might be seen to give legitimacy to decomposing the nature of science into a set of atomistic components that might, at worst, be taught in isolation in a highly decontextualized manner. Many of the participants recognized that the account of science represented by these themes may be limited, and it might be difficult to specify such aspects clearly and unambiguously. Indeed, from our analysis of the comments of the participants, many felt that some of the ideas were intertwined and not resolvable into separate propositions. Our second conclusion, therefore, is that many of the aspects of the nature of science represented by the themes have features that are interrelated and cannot be taught independently of each other. This finding suggests that, although the research process has required the separation and resolution of these components to weight their significance and import, there is no agreement that they should be communicated and represented in that manner.

It is also important to recognize that the definition of consensus we have used has drawn an arbitrary line. Using the same criteria of a mean rating of 4 and a stability of <33% shift between the two rounds, over 50% of participants considered several other themes to warrant inclusion in the curriculum. Specifically, these were: Science and Technology (65%), Moral and Ethical Dimensions in the Development of Scientific Knowledge (61%), Empirical Base of Scientific Knowledge (61%), Cumulative and Revisionary Nature of Scientific Knowledge (61%), Observation and Measurement (56%), Characteristics of Scientific Knowledge (52%), and Specific Methods of Science (52%).

This suggests that these data represent the participants' gradation of importance of the themes rather than a singular definitive account in which only certain atomistic features are to be addressed and other aspects ignored. In short, the nine themes represent the basic minimum that any simplified account of science should address. The other themes, although significant, are additional components to be included in more complex or more sophisticated accounts, or where such aspects emerge naturalistically from the context of study, whatever that might be.

Discussion and Implications

This survey of a panel of diverse experts has produced results that raise several issues about curriculum design, instruction, and implementation. Many themes emerging from this study bear similarity to those included in current National Curricula or National Standards. Table 4 shows

Table 4
Comparison of themes emerging from this study with those from McComas and Olson's (1998) study of national standards

McComas & Olson	Delphi Study
Scientific knowledge is tentative	Science and Certainty
Science relies on empirical evidence	Analysis and Interpretation of Data
Scientists require replicability and truthful reporting	Scientific Method and Critical Testing
Science is an attempt to explain phenomena	Hypothesis and Prediction
Scientists are creative	Creativity Science and Questioning
Science is part of social tradition	Cooperation and collaboration in the development of scientific knowledge
Science has played an important role in technology	Science and Technology[b]
Scientific ideas have been affected by their social and historical milieu	Historical Development of Scientific Knowledge
	Diversity of Scientific Thinking
Changes in science occur gradually	
Science has global implications	
New knowledge must be reported clearly and openly[a]	

[a] While this theme did emerge from round 1 of the study, it was not considered important enough by the participants for inclusion in top rated themes in subsequent rounds.

[b] This was not one of the 9 themes achieving consensus but came close with 65% rating its importance 4 or higher.

a tentative comparison of the most prevalent ideas about science found in those documents (McComas & Olson, 1998), i.e., ideas found in six or more national curriculum documents, and those emerging from this study. In the table, themes emerging from McComas and Olson's work that are similar to themes emerging from this work have been juxtaposed.

Our data clearly have many similarities with the data of McComas and Olson. That there is a measure of agreement between the views developed for consensual documents and the empirical findings from this study strengthens the case for including an account of the nature of science in the school science curriculum, albeit a vulgarized one. Our view is that the importance of this study lies in the fact that it provides a body of empirical data drawn from a panel of experts which challenges the case made by Alters (1997) that no singular consensual view exists. Therefore, we contend that the nature of science can no longer be marginalized on the basis that there is little academic consensus about what should be taught.

Although there clearly is an ongoing debate within the academic community about the nature of science, we feel that the essence of this debate is about the extent to which cultural and subjective factors impinge on the practice of science. A recent helpful edited volume (Labinger & Collins, 2001) with contributions from many of the main protagonists in the science wars debate suggests that the distinction is more a methodologic one rather than a substantive difference over the nature of subjectivity and objectivity. None of the consensually agreed-upon themes emerging from this study impinge on the focus of that debate. Although it is an important debate for those with an interest in science, it has few insights to offer into the practices, methods, and processes of science that any school science curriculum would seek to expose and communicate to students. An interesting test of the validity of our findings would be if they would obtained 90% approbation from a larger community of similar individuals from whom they have been derived.

We contend, however, that the components that emerge from this study and that of McComas and Olson pose a challenge to curriculum designers and to science education. For instance, the latest version of the English Science National Curriculum (DfEE, 1999) provides some recognition of the significance that should be given to ''ideas and evidence in science'' with an eponymous component which might otherwise be termed the nature of science or ''ideas-about science'' (Millar & Osborne, 1998). Comparing the English National Curriculum requirements with the results of our study, it is possible to see elements of most of the major nine themes. It might be tempting, therefore, to think that the treatment of the nature of science is satisfactory in the existing English science curriculum. However, at least within the English curriculum, there is no treatment of one of the major themes from the Delphi study: the Diversity of Scientific Thinking. Few curricula have recognized the fundamental division Rudolph (2000) made between historical reconstruction and empirical testing. The latter, which is largely the domain of the physical, chemical, and molecular sciences, stands in contrast to the process of historical reconstruction in which the intellectual product is an explanatory mechanism for the chronologic sequence of past natural occurrences. As Rudolph argued:

> Such a chronology, be it a phylogenetic history of various species or a record of climate changes in the Earth's history, is eminently particularist, always consisting of a chain of historically contingent events. The immediate goal in this case is not the development of a model, but rather the establishment of reliable record of what has occurred and when. (2000, p. 410)

Yet, school science is dominated by the empirical and exact sciences of physics, chemistry, and biology. Notable for its absence, for example, is a treatment of correlational methods which provide the basic methodology of medical trials and which are, moreover, a common feature of media reports of science.

Hence, our data and those of McComas and Olson suggest that there are significant elements of a minimal account of the nature of science missing from most curricula. Remediation of this deficiency will be possible only by allocating substantially more than 5% assessment weighting currently offered, for example, by the English curriculum. Coupled with the arguments advanced by Fuller (1997) that teaching students about the nature of science is as important as developing a knowledge of its content, if not more so, these findings lend support to the view that teaching the nature of science needs to become a core rather than a marginal part of the science curriculum.

Second, comparison of our data with those of McComas and Olson suggests that, although there is some overlap, there are components present in each study which are missing from the other. In short, and perhaps not surprisingly, no one method and no one group of individuals can provide a universal solution as to what should be the essential elements of a contemporary science curriculum. Rather, we do not regard this work or any other as definitive but simply a contribution to establishing a body of knowledge and common understandings about the essential elements of any account of science offered to school students. Moreover, as we have already commented in our discussion of the interrelationships between themes emerging from our study, our data suggest that many themes identified are not always resolvable into mutually independent aspects. For instance, teaching about science and certainty invariably means also inspecting the reliability and validity of empirical evidence.

Our findings further suggest that it might be a mistake to attempt to delineate a curriculum in terms of a requirement to teach the components of the nature of science separately. Rather, its teaching can perhaps best be addressed through sets of well-chosen case studies of either a historical or contemporary nature and by more explicit reflection and discussion of science and its nature—an aspect that should emerge naturally from the process of scientific inquiry that is a normal feature of much classroom practice. Thus, the principal value of these, or any set of themes, would be to act as a curriculum checklist to see that the activities in the curriculum provide sufficient opportunity to introduce, elaborate on, explore, and develop students' understanding of these components of science and its nature. However, in our view, it is not sufficient to suggest that the nature of science can simply be taught by a random selection of case studies. For how is the teacher to decide which are apt and which are inappropriate? Such an approach will still require an analysis of the content of the domain to guide the selection of cases—guidance which we think this research offers.

Many of the themes emerging from our study fall under the umbrella of the Methods of Science (Experimental Methods and Critical Testing, Creativity, Science and Questioning, Diversity of Scientific Method, and Analysis and Interpretation of Data). Two themes (Historical Development of Scientific Knowledge and Science and Certainty) are aspects of the Nature of Scientific Knowledge and there is only one under the heading of the Institutions and Social Practices of Science. One interpretation of this outcome is that the panel felt that an emphasis on the Methods of Science offered the most appropriate grounding in the nature of science for students in the science curriculum for 5- to 16-year-old children. An alternative view is that this outcome can be explained, in part, by the fact that many participants may have seen aspects of the institutional and social practices subsumed within the other themes. However, it does invite the question of why so many of the ideas of contemporary scholarship about the nature of science are absent. For instance, neither the themes emerging from this study nor those of the national curriculum documents place much emphasis on the role of theory, explanation, and models. They do not, for instance, represent a more contemporary view of science such as that offered by Giere (1991), who portrayed science as a multidimensional interaction among the models of scientists, empirical observation of the real world, and their predictions. However, the question to our participants was phrased as, "What, if anything, should be taught about the methods of science/

the nature of scientific knowledge/the institutions and social practices of science?" In short, we were asking for a minimal description. We suggest that the omission of other components is simply owing to the fact that they were regarded as too complex or too contentious for inclusion.

Given both the support for the themes and the perceived difficulties of curriculum design, the question arises as to how these statements might be operationalized into teaching strategies, activities, and material to support their teaching. One challenge is how such themes can become part of the instructional sequence. To what extent, for instance, can these themes be taught directly as part of discrete lessons or should they permeate all science lessons—an issue raised by some Delphi participants. Even those themes that might be considered integral components of the existing curriculum, such as analysis and interpretation of data, are often poorly covered and, research would suggest, poorly understood by students (Gott & Johnson, 1996; Lubben & Millar, 1996; Watson & Wood-Robinson, 1998). Whereas inquiry-based approaches, investigations, or practical work will certainly address many of the themes in the Methods of Science category, unless there is some careful mediation on the part of the teacher across lessons to highlight the methodologic features of these activities and their generic nature explicitly, many aspects of a more accurate picture of the nature of science may be glimpsed only partially, if at all, by students. The next phase of work with 12 teachers (3 Grade 6, 4 Grade 8, and 4 Grade 10) has sought to explore these problems. With these teachers we have attempted to see how the themes can become an integral part of their teaching and the difficulties that emerge (Bartholomew, Osborne, & Ratcliffe, 2002). However, we are under no illusions that the task of transforming the existing science curriculum will require more than the kinds of tentative explorations that have been attempted over the past 50 years.

This study has shown that within the broad community with an interest or engagement in science and science education, there exists a consensus about the core features of an account of the nature of science. It therefore suggests that one common obstacle to teaching about science is without foundation. Hence, we see this work as providing another body of empirical evidence to buttress the case for placing the nature of science and its processes at the core rather than the margins of science education. The detailed responses of the participants provide, in addition, valuable pointers to the content of such teaching. Although some may object that teaching a vulgarized account of science runs the risk of misrepresenting the essential elements of scientific practice and the values of the scientific community, we prefer to stress the positive aspect of such an account: that it can provide a basic understanding of the processes and practices of science and of the nature of the knowledge that these produce. Not only will such an account help young people make sense of the science that impinges on them in their daily lives, it may also lay the grounds from which a more sophisticated account may be developed in later life.

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Notes

[1] Good summaries of the main features of this debate can be found in Ruse (1999), Labinger and Collins (2001), and Hacking (2001).

[2] We acknowledge that one recent study (Lederman, Abd-el-Khalick, Bell, & Schwartz, 2002) suggests that some consensus does exist among experts. However, the experts were drawn only from science educators and historian or philosophers of science and there, and only nine were used.

[3] The use of an open-ended questionnaire to elicit views required a substantial commitment of time from each participant. Likewise, the document returned at each round required another body of time to read and respond. For this reason, all were paid an honorarium. The number of participants was therefore limited by the research funds available.

[4] The term *nature of scientific knowledge* is used here to refer to the distinctive features of the ontology and epistemology of science. It should not be confused with the term *nature of science*, which is used elsewhere in this article in its broad generic sense to refer to the methods of science, the nature of scientific knowledge, and its institutions and social practices.

[5] PU, S, SE, T, PS, and their numbers refer to individual people engaged in the public understanding of science, scientists, science educators, teachers, philosophers, and sociologists of science, respectively.

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