Curriculum Studies, Vol. 6, No. 2, 1998

Science Fiction: the continuing misrepresentation of science in the school curriculum

DEREK HODSON
Ontario Institute for Studies in Education, Toronto, Canada

ABSTRACT Despite the recent outpouring of writing on the history, philosophy and sociology of science, and its significance for science education, the school science curriculum continues to promote some grossly distorted views of science and scientists. Ten common myths are identified, seven of which are discussed in detail. The article concludes with a plea for teachers to present a more authentic view of science and a more appealing image of scientists as one step towards attracting a wider range of students to science.

On occasions, it is helpful to regard education in science as comprising three major elements: *learning science* – acquiring and developing conceptual and theoretical knowledge; *learning about science* – developing an understanding of the nature and methods of science, an appreciation of its history and development, and an awareness of the complex interactions among science, technology, society and environment; and *doing science* – engaging in and developing expertise in scientific inquiry and problem solving. This article is concerned with teaching and learning about science, an aspect of science education in which many modern courses continue to disappoint.

Despite extensive writing in this area in recent years [1], many students still leave school with deficient or distorted views of science (Ryan, 1987; Carey et al, 1989; Larochelle & Desautels, 1991; Duveen et al, 1993; Abell & Smith, 1994; Solomon et al, 1994, 1996; Lubben & Millar, 1996; Leach et al, 1997). Apart from concern that a significant aspect of humankind's cultural achievement should be so poorly understood, there are economic and sociopolitical implications to consider. There is ample evidence, for example, that the unfavourable image of science and scientists to which students are exposed is one of the major reasons why many students turn away from science at an early age (Holton, 1992). Thus, it prematurely limits the pool of talent from which future scientists are drawn, with potentially damaging effect on society's economic well-being. Moreover, failing to provide every student with an adequate understanding of the nature of science runs counter to the demand for an educated citizenry capable of responsible and active participation in a democratic society. A proper understanding of science and the scientific enterprise is a key component of scientific literacy, and is just as essential as scientific knowledge (i.e. conceptual understanding) in ensuring and maintaining a socially-just democratic society (Reid & Hodson, 1987).

Of course, much that students learn about science comes from sources outside the classroom: from movies, television, advertizing, books, magazines, museum visits, and so on. These influences are not my concern here. Rather, I am concerned with *curriculum* influences, with the messages that teachers give students about science and scientists. Sometimes, teachers take steps to emphasize particular views about science during class discussions and laboratory work; more often, however, such messages are not planned and are conveyed *implicitly*, through instructional language, biographical material and the characteristics of learning tasks, especially laboratory work and writing activities. Such messages collectively comprise a very powerful 'hidden' science curriculum (see Nott & Wellington, 1996).

My concern in this article is that many of the messages about science that we build into the curriculum (either consciously or unconsciously) are still locked in the mind-set of the 1960s and early 1970s. One of the legacies of that massive wave of curriculum development is that we promote and perpetuate some grossly distorted views of science and scientists. Among them is a complex of three myths:

Myth 1. Observation provides direct and reliable access to secure knowledge.
Myth 2. Science starts with observation.
Myth 3. Science proceeds via induction.

A number of science educators and philosophers of science have written at length on these myths (see, for example, Chalmers, 1982; Nadeau & Desautels, 1984; Duschl, 1988, 1990) and, as a direct consequence, some more recent science curriculum initiatives avoid these particular falsehoods, though clearly that is not universally the case. It is not my intention to discuss these three long-standing myths here. Rather, this article concentrates on the elaboration of *seven* further myths promoted through the science curriculum.[2] Correcting these myths is an important part, though admittedly only a part, of presenting a more authentic view of science to students (see Martin et al [1990] for a discussion of other meanings of 'authentic science').

Myth 4. Experiments are decisive.

School science curricula are virtually unanimous in their views about the relationship between scientific knowledge and scientific method: the validity of all scientific knowledge claims is deemed to be judged solely in terms of consistency with observable and experimental evidence. Indeed, the very rationality and objectivity of science are held to be guaranteed by insisting that theories are subjected to experimental testing by others, and by the assumption that this testing is decisive. Thus, almost all school science curricula put enormous faith in the capacity of observation and experiment to provide reliable data for making unequivocal decisions about the validity of theories. Elsewhere, in an examination of some of the ways in which we misrepresent to students both the nature and the role of experiments (Hodson, 1988), I made the following three points.

x Scientific knowledge is at its most powerful and most effective when it is able to control and manipulate events. Indeed, many of the events observed during experiments do not occur in the natural world. In such circumstances, the experimental approach is able to obtain information that is considerably more detailed and precise than that arising from passive observation.

x Experimentally-driven science is not the only kind of science. While experiments often provide scientists with a powerful means of acquiring and testing knowledge, they are neither sufficient in themselves to provide theoretical knowledge, nor are they always necessary. Many fields of scientific endeavour deal with events that are remote and inaccessible in time and space, and so make little or no use of experiments. Hence, theoretical conjectures have to be confirmed or refuted by *uncontrived* observations. In some fields, experimentation may, in principle, be possible, but is ruled inadmissible for ethical reasons. In these cases, as in science generally, correlational studies play a much more significant role than conventional science curricula would imply.

x The power that results from close control is also the major weakness of the experimental method and a potential trap for the unwary. Experiments are conducted within a particular theoretical matrix, which governs scientists' perceptions of the problem, determines the experimental design, influences the interpretation of results and so on. Theories determine which experiments are regarded as legitimate and how they are to be conducted. For example, in gathering data to test a hypothesis, the form of the hypothesis, and the nature and method of data collection, are dictated by the very theory that is under test. In other words, no theory-independent experiments are possible.

These three points serve to remind us that in seeking to give students an understanding of the nature and purpose of experiments, we must be wary that we do not reinforce the several prevalent falsehoods about the role and status of experiments. It is not just non-scientists who hold to beliefs that the experimental method is universally essential to science and that all science results from experimentation, a view that is particularly prominent in the world of advertizing ("experimentally proven to wash whiter”!). Science teachers, themselves, sometimes ‘forget’ that many aspects of the science they teach are not susceptible to direct experimental study, that many major theoretical advances in science did not result from experimentation, and that many theories were developed and substantiated by indirect means – consistency with other theoretical systems, use of ‘thought experiments’ and correlational studies, for example – rather than by experimentally-based observation (Hacking, 1983).

Many school science curricula project the view that a hypothesis can be rejected and, by inference, another accepted, on the evidence provided by a simple experimental test. Indeed, a number of curricula suggest that this is the *only* role of experiments. It is commonplace for teachers to insist on a clear demarcation between hypothesis generation and hypothesis testing. This kind of naive interpretation of the Popperian notion of falsificationism carries with it the assumption that theory-independent evidence is available and that unambiguous testing is possible. In reality, scientific experimentation is not a simple matter, and science education that portrays it as such is misleading. If (passive) observation is theory-dependent – a view that many science curricula now attempt to establish – how much more so is the active, interrogative observation of contrived events that constitutes experimentation? It is important that students realize that every experiment is set within a theoretical matrix, a procedural matrix (a current ‘method’ or ‘practice’ underpinned by theories and conventions about how to conduct, record and report experiments) and an instrumental matrix (involving various theories of instrumentation). It is theoretical understanding that gives both purpose and form to experiments.

Furthermore, if theories are incommensurable, a point on which many philosophers of science agree, there can be no crucial experiment to decide between them. Such experiments would require competing theories to make mutually exclusive predictions about the same events. In practice, competing theories address the world in different ways (often using different concepts) and, therefore, make different kinds of predictions about observable phenomena. Usually, therefore, it is possible only to provide an experimental evaluation of a theory *on its own terms*. In such cases, decisions between rival theories have to be made on criteria other than empirical validity (see below).

The critical role of experiments is an important one in science, but theories are only abandoned when there is compelling evidence (long-standing and striking at the fundamental core of the theory) and/or when an alternative and more promising theory becomes available. It is misleading to present students with the idea that theories are abandoned because of a few negative results. In practice, all theories have to live with anomalous data; it is a natural feature of science. We seriously mislead students when we pretend that the kinds of experiments they perform in class constitute a straightforward and reliable means of choosing between rival theories. Because experiments are perceived, designed and executed within a particular theoretical matrix, considerable judgement is involved in appraising the significance of apparently falsifying evidence. Experimental testing of theories is not, therefore, an infallible, single step, but a multi-step decision-making process monitored and validated by the community. Experiment and theory have an inter-dependent and interactive relationship: experiments assist theory-building (by giving feedback concerning theoretical speculations) and theory, in turn, determines the kinds of experiments that can and should be carried out, and determines how experimentally-acquired data should be interpreted. Both experiment and theory, then, are *tools for thinking* in the quest for satisfactory and convincing explanations.

Myth 5. Science comprises discrete, generic processes.

This assumption underpins the so-called Process Approach to science education. This approach, which is subjected to lengthy critical examination by Wellington (1989), is rooted in a series of arguments that content does not really matter, especially at elementary school level, and that what is of paramount importance is experience of the *processes* of science.[3] Because they are held to be discrete, context-independent activities, these various processes (observation, classification, inference, and so on) are said to be generalizable and transferable (Screen, 1988).

Fundamental to the Process Approach – and common to many other curricula, too – is the assumption that a distinction can be drawn between ‘raw data’ (and its manipulation) and our theoretical interpretation of it – that is, between ‘facts’ and theories or, as the Ministry of Education (Ontario) (1987) says, “between observation and inference”. Abruscato’s (1988) book *Teaching Children Science*, for example, asserts that “Nothing is more fundamental to clear thinking than the ability to distinguish between an observation and an inference”. Superficially, this distinction sounds fine, and seems to relate to what we usually consider to be a major aspect of good scientific inquiry: that scientists should have respect for the evidence and not claim more from their investigation than the facts will support. However, I do not believe that such a distinction exists in any absolute sense. Indeed, when a new theory appears, or when new instrumentation techniques are developed, our notion of what is a theoretical statement and what is an observation statement may change. As Feyerabend (1962) points out, observation statements are merely those theoretical statements to which we can assent quickly, relatively reliably and without calculation or inference, because we all accept, without question, the theories on which they are based. In other words, the demarcation between observation and inference shifts with experience, and where particular individuals ‘draw the line’ depends on their knowledge, level of experience, and familiarity with the phenomena or events being studied. In the familiar exercise of observing a burning candle, for example, all but very young children know that the liquid on the top of the burning candle is molten wax because they have no doubts about the theoretical assumptions that impregnate such an observation. To insist that they regard it as an inference is to be pedantic to a degree that can be counter productive to good science (Geddis, 1991).

What I am argueing is that when theories are well understood and taken-for-granted, they *provide* an observation language. Terms like *reflection* and *refraction, suspension* and *solution, contraction* and *expansion* all carry with them an inferential component rooted in theoretical understanding. Unless some theory is taken-for-granted, and the theory-loaded term used for making observations, we cannot make progress. We would for ever be trying to return to simpler and allegedly (but mistakenly so) theory-free terms. Secure conceptual understanding is the ‘trigger’ for changing the language and for making progress towards more sophisticated understanding. So that with the general acceptance of a theory of solubility, for example, students see things *dissolve*, where previously they saw them *disappear*. In addition, once they understand that there is an important conceptual difference between *dissolving* and *melting*, they see why it is important to be careful in their use of the terms. Young children, without this conceptual knowledge, will continue to refer to sugar and salt ‘melting’ in water. They have no reason to do otherwise. When an observational exercise from earlier in the course is repeated, the new description employs observational language that includes previously unknown theoretical notions. Perhaps solids can now be observed to melt, sublime or decrepitate on heating, whereas previously they just *changed*. All three of these new terms include theoretical inference. Through such reflective experiences, students can be made aware of the ways in which their own observational skills change and develop as their theoretical understanding becomes more sophisticated. Discussion of the theoretical assumptions underpinning the design of common laboratory instruments can help students to appreciate that the supposed distinction between objective observation and theoretical inference is less clear than some science textbooks would assert, and is more a characteristic of their own stage of conceptual understanding, and their confidence in that knowledge, than a demarcation between two processes of science.

Arguments similar to those for the theory-ladenness of observation extend to all the other processes of science, such as classifying, measuring, hypothesizing and inferring. One has to classify and measure something, rather than something else; one has to hypothesize about particular entities or events. It simply is not possible to engage in these processes independently of content. Moreover, the way one classifies, measures and hypothesizes, and one’s level of sophistication in doing so, depend crucially on one’s theoretical understanding. Science education is not about teaching students to observe, classify, measure and hypothesize *per se*. They can already do that perfectly well, and have been doing so since long before they came to our science lessons. Moreover, they continue to do so every day in their lives outside the laboratory. What school science is concerned with is *scientific* observation, *scientific* classification and *scientific* hypothesizing. What makes these processes *scientific* is the utilization of relevant and appropriate science concepts in pursuit of scientific purpose.

Scientific classification, for example, is not just a matter of noting similarities and differences – or it would be sufficient in science lessons to classify banknotes and postage stamps (using criteria such as country of origin, colour, size and style of illustration). Rather, it involves the application of scientifically significant and appropriate categories, suited to the purpose for which the classification is being carried out. Different purposes demand different criteria, and may involve different theoretical understanding. Consequently, successful classification is a matter of recognizing and using appropriate theory-based categories. It depends crucially on the knowledge, experience, assumptions and expectations about purpose that the classifier brings to the task. Any classroom activity involving classification or 'looking for patterns' is, therefore, inextricably linked with theory (appropriate concepts for classification) and purpose.

So it is with measuring, predicting, collecting data, recording data, and all the other processes of science. None of them can be carried out without a substantial measure of theoretical knowledge. The notion that *predictions* can be made independently of content, for example, is just too absurd to be seriously contemplated. What can possibly constitute the basis of a prediction other than some good understanding of the phenomenon or event under consideration? Without theoretical understanding, predictions are no more than 'blind guesses', and there is little of educational value in encouraging children to make those. McNairy (1985) says that whether a prediction is correct or not does not matter. I agree. But what *does* matter is that the student has good (scientific) reasons for making a particular prediction, can establish a chain of argument from her or his current understanding to the prediction, and knows enough about the methods of scientific inquiry to know what would constitute an appropriate test of that prediction. Nor can the control of variables be achieved without substantial knowledge of the phenomenon being studied. How would a theory-free experimenter know what the variables are likely to be? In a state of ignorance, no variables can be controlled, except fortuitously. Clearly, the planning of any experiment in which variables are carefully and sytematically varied is a theory-driven and theory-impregnated activity.

The theory-impregnated nature of scientific processes creates enormous problems for the notion of transferability, which is, of course, a central principle of the Process Approach.

> *If process skills are not tied to the context in which they are learned, they can be taught in a specific content area and subsequently used to solve problems from other areas within science, or from subjects such as social science or mathematics. The potential generalizability of the process skills represents an important reason for emphasizing their development and use.*
> *(Tobin & Capie, 1980, pp. 590-591)*

A corollary of asserting that experience of scientific processes in any context is as significant as experience in any other is a commitment to the notions that (i) no particular conceptual understanding is significant, and (ii) the ability to observe, classify and measure in one context can be taken as indicative of a student's capacity to do so in an entirely different context. These arguments have been extended to an absurd degree by those who advocate skills-based testing in science. Not only is this approach philosophically unsound, for the reasons given above, it is educationally worthless (because it trivializes learning), pedagogically dangerous (because it encourages bad teaching), professionally debasing (because it de-skills teachers) and socially undesirable (because of powerful hidden messages concerning control and compliance) (Hodson, 1993a). The absurdity of the claim that competence in one skill, such as observation or measurement, can be learned in a particular context and subsequently transferred to an entirely different one, with no apparent loss of capability, has been addressed elsewhere (Hodson, 1992). The arguments will not be rehearsed here, save to note that acceptance of such a notion in the world outside school would suggest that we happily submit to a brain operation carried out by a specialist in obstetrics, or psychiatry. In reality, the context in which skills are acquired is crucial to the proper performance of that skill and to our confidence in the practitioner.

Myth 6. Scientific inquiry is a simple, algorithmic procedure.

A major absurdity of the Process Approach referred to in the previous section is the assumption that once students have acquired the separate process skills of observing, classifying, measuring, and so on, they can put them together into a procedure for *doing science*. In other words that doing science consists in the sum of its parts and is no more than the sum of its parts. In short, scientific inquiry comprises an algorithm. For example, Gagne (1963, p. 152) argues that "engaging in enquiry of a successful, productive and useful variety can be undertaken when [and, presumably, *only* when] the individual has acquired a store of broad and critical knowledge, and this in turn can be acquired when [and only when] he [sic] has learned some prerequisite but very important fundamental capabilities". For Gagne, these "capabilities" are, of course, the basic processes of science. A student below about school grade 11 level, he argues, should be given laboratory exercises rather than encouraged to undertake independent, holistic enquiries, because "if he is encouraged to do the latter, he will fail because he doesn't *know* enough to behave like a scientist" (p. 151) and "one doesn't learn to be a scientist, or to appreciate science by pretending to be a scientist" (p. 152). The 'step-up' model of the Scottish TAPS 1 scheme (Bryce et al, 1987) seems to imply a similar position. Hayes (1982: 2) leaves no doubt about her commitment to an algorithmic method for 'doing science':

> *The sequence in any scientific investigation is the same:*
> *observation, by as many ways as are relevant, sorting into groups*

> *with similar properties so that patterns emerge, prediction of what will happen under different conditions, experimentation to test those predictions and finally, an explanation of what happened .... These are the bones of science at any level.*

In my view, there are two major problems with this step-up model. First, there is no empirical research evidence to substantiate the claim for its value as a teaching and learning strategy. Secondly, and more importantly, the model itself is fundamentally flawed and does not constitute a faithful or adequate description of scientific inquiry. These allegedly discrete, content-free processes do not collectively constitute a procedure for doing science. Being able to carry out one, or several, decontextualized tasks focusing on observation, classification or measurement says very little about one's capacity to conduct a real scientific investigation. It is sometimes the case that students who are able to perform adequately on such de-contextualized tasks are unable to integrate these skills and abilities into a coherent and effective strategy for scientific investigation. Conversely, many who perform poorly in these sanitized tests can engage in interesting and successful scientific inquiry when they are suitably encouraged and given the freedom and support to follow their interests.

There is little in the contemporary philosophy of science literature to support the notion that scientific method can be easily and unambiguously described, or that it comprises the application of an invariable sequence of well-characterized steps to be applied in all circumstances. Science has no *one* method, no set of rules or sequence of steps that can and should be applied in all situations. However, this should not be taken as implying that science has *no* methods. Science does have methods, but the precise nature of those methods depends on the particular circumstances: the nature of the problem, the phenomenon or event under scrutiny, the theoretical understanding of the inquirer, the scientific 'hardware' available and so on. In conducting a particular investigation, scientists choose an approach they consider to be appropriate to the particular task-in-hand by making a selection of processes and procedures from the range of those available and approved by the community of practitioners. Furthermore, scientists refine their approach to a problem, develop greater understanding of it and devise more appropriate and productive ways of proceeding *all at the same time*. As soon as an idea is developed, it is subjected to evaluation (by observation, experiment, comparison with other theories, etc). Sometimes that evaluation leads to new ideas, to further and different experiments, or even to a complete re-casting of the original idea or reformulation of the problem. Thus, almost every move that a scientist makes during an inquiry *changes* the situation in some way, so that the next decisions and moves are made in an altered context. Consequently, scientific inquiry is holistic, fluid, reflexive, context-dependent and idiosyncratic, not a matter of following a set of rules that requires particular behaviours at particular times.

Students will no more discover these methods for themselves than they will discover the ways in which conceptual knowledge in science is organized – the hopelessly unrealistic goal of the 1960s discovery learning movement (Wellington, 1981; Hodson, 1996). They have to be taught. Gott & Duggan (1995, 1996) focus on some of the features of experimental inquiry [4] that can be systematically taught, identifying what they term the "concepts of evidence" essential to an appraisal of the reliability and validity of experimentally-gathered data. Those associated with *experimental design* include variable identification, fair test, sample and variable types; those associated with *measurement* include relative scale, range and interval, choice of instrument, repeatability and accuracy; those associated with *data handling* include tables, graph types, patterns and multivariate data. However, in the real world of scientific practice, success in the creative enterprise of doing science comes to those who can choose a course of action that is well-suited to the situation. There are no rules for making these kinds of choices; there is no algorithm that can be applied. All decisions are local – determined by the particular circumstances of individual investigations – and, therefore, *idiosyncratic*. As in games playing, success comes to those who can improvize and exploit opportunities, rather than to those who slavishly seek to follow strict guidelines. As Albert Einstein is reputed to have said, to be a successful scientist it is necessary to be an unscrupulous opportunist!

Moreover, this untidy, uncertain and idiosyncratic activity depends for its success on the *tacit* knowledge of the inquiring scientist, knowledge that links what the inquirer knows, in a conscious sense, with what she or he feels and experiences. It is the kind of knowledge that good games players, chess masters, expert musicians and gifted teachers have, and use all the time in their day-to-day work. Often, these skilled practitioners cannot analyse, describe and explain what they do; they just do it – intuitively. This kind of intuitive, tacit knowledge is a key element in the art and craft of the creative scientist.

If the ways in which scientists work are not fixed and not entirely predictable, and if they involve a component that is experience-dependent in a very personal sense, they are not teachable by conventional didactic methods. That is, one cannot learn to do science by learning a prescription or set of processes to be applied in all situations. The only effective way to learn to do science is by doing science, alongside a skilled and experienced practitioner who can provide on-the-job support, criticism and advice. As Ravetz (1971) has commented, learning to do science occurs "almost entirely within the interpersonal channel, requiring personal contact and a measure of personal sympathy between the parties. What is transmitted will be partly explicit, but partly tacit; principle, precept, and example are all mixed together." It is here that the notion of *apprenticeship* is useful. As Jean Lave (1988) says: "Apprentices learn to think, argue, act, and interact in increasingly knowledgable ways with people who do something well, by doing it with them as legitimate, peripheral participants". For Lave, apprenticeship is not just a process of internalizing knowledge and skills, it is the process of becoming a member of a community of practice. Developing an identity as a member of the community and becoming more knowledgeable and skilful are part of the same process, with the former motivating, shaping and giving meaning to the latter.

> *Newcomers become oldtimers through a social process of increasingly centripetal participation, which depends on legitimate access to ongoing community practice. (Lave, 1991, p. 68)*

When they are given opportunities to participate peripherally in the activities of the community, newcomers pick up the relevant social language, imitate the behaviour of skilled and knowledgeable members, and gradually start to act in accordance with the community norms.

If these arguments from situated cognition theory hold, students should come to understand scientific inquiry and to carry out scientific inquiries properly and more successfully by conducting scientific inquiries – simple investigations at first, probably chosen from a well-tried list of ‘successful’ investigations designed and developed by the teacher, but whole investigations nevertheless, and always under the watchful eye of an experienced and expert practitioner, acting in a critical and supportive role. Then, as confidence, skill and knowledge grow, progress can be made to more complex, more challenging and more open-ended investigations. What seems beyond dispute is that students need a carefully sequenced programme of investigative activities, and a programme of skilled teacher modelling, instructive intervention and support. Qualter et al (1990) describe in some detail how such a programme can be organized. The amount and extent of intervention necessary is not easy to judge. Too early and too directive an intervention and students will, thereafter, wait for teachers to tell them how to do it. Too late and too vague an intervention and students are likely to give up in exasperation. The goal is that, eventually, students will be able to proceed independently: choosing their own topics for inquiry and approaching them in their own way. However, the teacher’s role is still a crucial one: role model, learning resource, facilitator, consultant and critic.

Myth 7. Science is a value-free activity.

If it is not possible to perform critical experiments capable of furnishing theory-free data (see discussion of myth 4), it follows that there are no purely empirical criteria for establishing the superiority of one paradigm over another. In other words, science is not entirely objective and rational (at least not in the sense that rationality is conventionally portrayed in science education). A message that we do not build into the science curriculum, nor into the public image of science, is that scientific theories are empirically under-determined. Empirical adequacy is insufficient, in itself, to establish validity. Consistency with the observable facts does not confer truth status on a theory. Such consistency simply means that a theory *may* be true, but so may lots of other theories that also correspond with the observations (Duhem, 1962). Moreover, empirical inadequacy is frequently ignored by individual scientists fighting passionately for a well-loved theory (Mitroff & Mason, 1974) and is often considered subordinate to the 'context of discovery' by the community-appointed validators (Knorr-Cetina, 1983). Additional factors that may play a part in bringing about the shift of paradigm allegiance that constitutes a scientific revolution include:

x Elegance and simplicity (the aesthetics of science).
x Similarity and consistency with other theories.
x 'Intellectual fashion', in the sense of compatibility with trends in other disciplines.
x Social and economic considerations.
x Cultural considerations.
x The status of the researchers.
x The views of 'significant others' – influential and powerful scientists, journal editors, publishers and so on.
x The priorities of research funding agencies.

If one takes the view that science is a communal activity, and that the ideas of particular scientists only become accepted as scientific knowledge when they achieve consensus within the community of scientists, it follows that many of the sociological, psychological, political and economic issues that influence individuals could, and sometimes will, influence the decisions that the community makes. By failing to address these influences, the simple-minded accounts of theory acceptance and rejection presented in school science textbooks are insulting to students and often flatly contradict what they read elsewhere about real scientists like Galileo, Albert Einstein, Barbara McClintock, Francis Crick and Jim Watson. What these accounts omit is *people,* and their views, attitudes and prejudices. By contrast, Fuller (1988) writes about the rather wider issues that influence the ways in which scientists present their own work and evaluate each other's. Prominent among them are strong presuppositions or feelings about the way things work, sometimes before evidence is collected, sometimes despite the evidence that has been collected (Holton, 1978, 1986). Perhaps this is another aspect of the scientist's tacit knowledge described in the previous section and so contributes to what we might term *scientific connoisseurship.*

It would be more appropriate for the school curriculum to emphasize the ways in which knowledge is *negotiated* within the community of scientists by a complex interplay of theoretical argument, experiment and personal opinion, than to try to project the view that science is independent of the society in which it is located. Criteria of judgement include factors outside pure logic and empirical adequacy, including the social, economic, political, moral and ethical factors that impact on the decision-makers. In other words, science is not value-free and 'people-proof'. As Robert Young (1987) says:

> *Science is not something in the sky, not a set of eternal truths waiting for discovery. Science is practice. There is no other science than the science that gets done. The science that exists is the record of the questions that it has occurred to scientists to ask, the proposals that get funded, the paths that get pursued ... Nature 'answers' only the questions that get asked and pursued long enough to lead to results that enter the public domain. Whether or not they get asked, how far they get pursued, are matters for a given society, its educational system, its patronage system and its funding bodies.*

In providing alternative insights into the generation and validation of scientific knowledge, the claims of contemporary sociology of science (Bloor, 1976, 1991; Latour & Woolgar, 1979, 1986; Brannigan, 1981; Collins & Pinch, 1982, 1992; Mulkay & Gilbert, 1984; Traweek, 1988; Collins, 1991) constitute an enormous challenge to the current image of science in the school curriculum, and should be taken seriously by all science educators. What is important is that we achieve a sensible balance between the view that science is absolute truth ascertained by value-free, disinterested individuals using entirely objective and reliable methods of inquiry – a view that, unfortunately, is still quite widespread in school science curricula – and the dangerously relativist view that 'scientific truth' is that which is in the interests of those in power or, as Slezak (1994) lampoons it, "truth is what you can get away with". While we may reject the notion that science is entirely determined by a combination of scientists' self-interests and political expediency, we should recognize that it is profoundly influenced by social, economic and moral-ethical considerations, and so is, to a large extent, a product of its time and place. We should also recognize that many of the products and procedures of science are inherently value-laden: a nuclear missile and a technique for *in vitro* fertilization, for example, cannot be used for ends other than those for which they were designed and the claim that a product was developed and 'made safe' through experiments on laboratory animals is a constant reminder of the value-laden nature of much of what scientists and technologists do.

While it would be absurd to claim that scientific knowledge is less reliable or valid simply because it is developed in furtherance of particular interests, or that the products of scientific inquiry and theory-building cannot be understood apart from their sociohistorical contexts, appreciation of the sociocultural milieu within which particular scientists work (or worked) provides the context for understanding their priorities, working styles and criteria of judgement. This applies just as much to a full understanding of the elegant rationalist work of Isaac Newton as it does to understanding the theory of phrenology, a set of beliefs and values held by many prominent scientists and non-scientists in Victorian England (Hodson & Prophet, 1986).

Myth 8. Science is an exclusively Western, post-Renaissance activity.

In lamenting the distorted history of science usually presented in school, Dennick (1992) remarks:

> *Throughout European history since the Renaissance there has been a tendency to disparage and down grade the discoveries and achievements of other cultures and historians have been very prone to give credit where it is not due.*

He cites Needham's (1954, 1969) assertion that the inventions he regards as the three most important of the millennium (paper-making and printing, gunpowder and the navigational compass) were each used in China several hundred years before their alleged discovery by Westerners. Chinese science is often dismissed by writers of school science texts as 'mere technology', creating the impression that it was little more than haphazard trial and error ('suck-it-and-see', as my fellow Lancastrians would say) or, at best, was a series of chance discoveries.

> *... throughout ancient Chinese, Egyptian, and other cultures of the time, there was, in effect, no real attempt to understand or to generalize. If devices or explanations of the universe worked, they were accepted as best or true. (Loving, 1997, p. 440)*

Dennick (1992) reminds us that there is considerable evidence to the contrary; that Chinese science was theoretically driven (though its philosophical basis was radically different from that of Western science) and involved systematic observation and careful experimentation (Needham, 1981). Islamic, Indian and African scientific achievements have been similarly trivialized or falsely attributed to Weterners. For example, when the Arab contribution to the growth of science is mentioned at all, it is portrayed as no more than that of custodian of ancient Greek knowledge. Indeed, Sardar (1989) suggests that the Western world systematically plagiarized the work of Muslim scientists:

> *Piracy was so common that as early as the twelfth century a decree was issued in Seville forbidding the sale of scientific writings to Christians because the latter translated the writings and published them under another name.*

A similar fate befell much of Indian science (Kumar & Kenealy, 1992; Machwe, 1979). In addition, the agricultural theory and practice of the pre-Columbian societies of the Americas were subsumed within Euopean science without any acknowledgement (Weatherford, 1988). Even more serious in the context of arguments for an antiracist education is the systematic trivialization, distortion and suppression of African cultural history – a key element, of course, in the racist ideology that formerly legitimized slavery and colonial exploitation, and still serves to deny a sense of cultural identity to those of African descent. Despite the spectacular achievements of the civilzations of Ethiopia, Benin and Zimbabwe, for example, the myth is still propagated that significant

African history began with the imperialist invasions. Moreover, the great civilization of Egypt is often portrayed as Semitic, rather than African.

These falsehoods can be readily corrected through historical studies (Hodson & Dennick, 1994). For example, studies in the history of medicine, astronomy and technology – particularly rich in Islamic, Indian and Chinese exemplars – help to promote awareness that current scientific ideas are not derived solely from post-Renaissance Western societies. Nor is the debt that science and technology owes to diverse cultures only an historic one, as materials such as *Biographies of Black Scientists* (Watts, 1986) and *Black Pioneers of Science and Invention* (Haber, 1970) testify.

Myth 9. The so-called 'scientific attitudes' are essential to the effective practice of science.
Myth 10. Scientists possess these attitudes.

There is no doubt that the inculcation of 'scientific attitudes' has a high priority in the rhetoric of science curriculum development (Schibeci, 1984; Bhaskara Rao, 1992). It is commonly asserted that particular personal characteristics and attitudes are essential for the successful pursuit of science, and that scientists themselves all possess a particular cluster of attitudes and attributes, including superior intelligence, objectivity, rationality, open-mindedness, willingness to suspend judgement, intellectual integrity and communality. It is alleged that it is these 'scientific attitudes' that ensure that (i) all knowledge claims are treated sceptically until their validity can be judged according to the weight of evidence, (ii) all evidence is carefully considered before decisions are made, and (iii) the idiosyncratic prejudices of individual scientists do not intrude into the decision making. Of course, 'evidence' is always taken to be empirical evidence, agreement with the observed 'facts'. Thus, a genuinely scientific person is regarded as someone who makes decisions solely in terms of a dispassionate weighing of the empirical evidence (the 'facts').

More than 30 years ago, Roe (1961) suggested that scientists themselves do not possess these so-called 'scientific attitudes', although they think that they do. They, too, subscribe to the myths about the emotionally-detached, disinterested impartiality of the scientist. Or they continue to promote a false image because they perceive it to be in their interests. Incidentally, science teachers may also feel some vested interest in maintaining this image as a means of enhancing their status in school (Gaskell, 1992). Roe concludes: "The creative scientist, whatever his (*sic*) field, is very deeply involved emotionally and personally in his work". More recent work by Mahoney (1979) examined the extent to which scientists possess each of the characteristics so frequently ascribed to them. His conclusions are as follows.

x Superior intelligence is neither a prerequisite nor a correlate of high scientific achievement.

- Scientists are often illogical in their work, particularly when defending a preferred view or attacking a rival one.
- In experimental research, scientists are often selective, expedient and not immune to distorting the data.
- Scientists are probably the most passionate of professionals. Their theoretical and personal biases often colour their alleged openness to the data.
- Scientists are often dogmatically tenacious in their opinions, even when contradictory evidence is overwhelming.
- Scientists are not paragons of humility or disinterest. Rather, they are often selfish, ambitious and petulant defenders of personal recognition and territoriality.
- Scientists often behave in ways which are diametrically opposite to communal sharing of knowledge. They are frequently secretive and occasionally suppress data for personal reasons.
- Far from being a 'suspender of judgement', the scientist is often an impetuous truth-spinner who rushes to hypotheses and theories long before the data would warrant.

Mitroff & Mason (1974) distinguish two kinds of scientist: the *extreme speculative scientists*, who "wouldn't hesitate to build a whole theory of the solar system based on no data at all", and the *databound scientists*, who "wouldn't be able to save their own hide if a fire was burning next to them because they'd never have enough data to prove the fire was really there". What this and several other studies show is that, contrary to the textbook stereotype, the greater the scientist, the more likely she or he is to belie the myth of the disinterested, uncommitted individual, the "depersonalised and idealised seeker after truth, painstakingly pushing back the curtains which obscure objective reality" (Cawthron & Rowell, 1978).

Given that there are such discrepancies between the idealized picture of scientific attitudes and the characteristics of real scientists, one wonders why so many science curricula continue to promote these stereotypes. As Gauld (1982) remarks, "Teaching that scientists possess these characteristics is bad enough, but it is abhorrent that science educators should actually attempt to mold children in the same false image". There are numerous ethnographic studies of scientists-in-action able to provide a more faithful picture of laboratory life, and of the decision-making processes involved in scientific inquiry, and several examples of how to design classroom and laboratory activities capable of providing a more authentic view of science and scientific practice.[5]

In a sense, these views about necessary 'scientific attitudes' are grounded in the stereotype of scientific method represented by myths 1, 2, 3 and 6 (above). As discussed earlier, the extensive literature in the philosophy of science fails to identify a single, universally accepted description of scientific method. However, far from being dismayed by such lack of agreement, White (1983) regards it as an inevitable consequence of the complexity of the scientific enterprise, the myriad of possible starting points, and the differences in knowledge, experience and personality among scientists. Interestingly, children also regard diversity of approach as inevitable. They have no expectations of a particular method; it is teachers who create the expectation of a single method through their continual reference to *the* scientific method (Hodson, 1990) and, by extension, establish the belief that there are particular and necessary attributes for engaging in it.

However, our failure to identify a single, simple method does not mean that scientists have no methods. Feyerabend’s (1975) famous assertion that ‘anything goes’ implies the absence of a *prescribed* method, the absence of an algorithm, rather than the absence of methods. It should not be taken too literally. As Newton-Smith (1981) observes, “Lazing in the sun reading astrology is highly unlikely to lead to the invention of a predictively powerful theory about the constituents of the quark”. Implying that the world of the scientist is totally anarchic does students (and science) as gross a disservice as implying that science has a single, all-powerful, algorithmic method (myth 6). Claims to scientific knowledge have to be publicly argued and publicly justified; the data on which conclusions are drawn and theories built has to be reproducible and the chain of evidence from premise to conclusion has to be clear. In other words, science does have methods and it does have criteria for judging the validity of knowledge claims, but their particular form depends on the particular circumstances: the matter under consideration, the conceptual structure within which the investigator frames the problem(s), the investigative techniques and instrumentation devices available, and so on. By making a selection of processes and procedures from the range of those available and approved by the community of practitioners, scientists choose a ‘method’ they consider to be contextually appropriate. There are no universal decision criteria for what to do and how to do it. All decisions are ‘local’ – determined by the particular circumstances of individual investigations – and, therefore, *idiosyncratic*. However, when the community comes to appraise a piece of scientific research, one of its criteria of judgement is a consideration of the methods employed. Were they well chosen? Were they satisfactorily performed? Could/should the investigation have been conducted differently?

If science is like this, the personal attributes for doing it successfully are likely to be very different from those we tell students in school. Successful scientists are likely to be those who are creative, inventive, daring and bold, not cautious, rule-bound and conventional.

Towards a Myth-Free Science

It has not been my intention to portray all scientists as self-serving, cynical opportunists, and it would be a disaster if the science curriculum did so. There is no doubt that scientists’ personal, political and religious views impact on the kind of science they choose to do; there is no doubt, either, that intuition, luck (both good and bad), self-interest, personal ambition, academic and publishing pressures will, from time to time, influence the way they do it. The key question is whether these are the predominant factors driving the scientific enterprise. There is bad science and there are bad scientists, but, in general, the public nature of scientific evaluation is a guarantee that they are, eventually, identified. Science as public knowledge is no guarantee, however, that the science produced will not be mistaken or that scientists will not, on occasions, ‘cut corners’ or be ‘selective’ in their presentation of data. Above all, I want to remind students that science is carried out by people, and that these people, like everyone else, have views, values, beliefs and interests. I want the curriculum to show students that these people (scientists) can be warm, sensitive, humorous and passionate. More importantly, I want them to realise that people who are warm, sensitive, humorous and passionate can still become scientists, though they are required to conduct their work in accordance with codes of practice established, scrutinized and maintained by the community of scientists.

In the old stereotyped school curriculum view of science, scientific knowledge exists ‘out there’ and scientists carefully, systematically and exhaustively collect information that reveals it. In this revised view, scientific knowledge is created in the minds of people and then scientists go out to look for evidence for and against the ideas they have generated. The old view sees science as being a slow, but powerful way of arriving at authoritative and certain knowledge of the world; scientific knowledge is ‘certain’, ‘proven’ and not to be questioned; scientific method has priority above all things. This revised view sees science as a creative, exciting and idiosyncratic activity, in which people invent ideas, have opinions, argue and fight for their ideas. The old view puts objective, open-minded observation and collection of factual data first, in time and priority. This alternative view puts ideas first. The old view requires people to subordinate themselves to a rigorous, algorithmic method. This alternative view allows individuals free rein to create and to use their imagination. The old approach is intolerant of opinion and does not allow for individualism; this alternative approach allows (requires, even) that individuals invent, create, have ideas and speculate – always provided, of course, that ideas are then subjected to rigorous testing and appraisal by others.

There is little doubt in my mind which view best reflects actual scientific practice. There is little doubt in my mind which view is likely to be more attractive to students. More than any other subject in school, science can allow students to be creative and inventive, if it is taught in accordance with the image articulated here. In practice, school science frequently does the reverse. It forces students to be conformist, it deprives them of opinion and ideas, it gives them authoritative knowledge that is not to be challenged.

Challenging these myths about science entails asking questions such as whether science is characterized principally by its area of concern, its concepts and theories, its methods of inquiry, or its criteria for judging the validity of knowledge claims. Other questions include: ‘What are the relationships among observation, theory and experiment?’ ‘What is the role and what is the status of scientific knowledge?’ ‘What are the underlying values of science (what Smolicz & Nunan, 1975, call its “ideological pivots”)?’ ‘Could any of these things be different without the activity ceasing to be science?’ ‘What might African science, Maori science or Feminist science be?’ ‘Do these terms mean anything?’ Finally, ‘If science could be different, should it be different?’ ‘Would these changes make it more accessible to students of ethnic minority cultures?’ ‘Would these changes have beneficial effect on the environment or the social fabric?’ By confronting these kinds of questions, students come to recognize that science is not the simple straightforward business that is part of its public image. Thus, they are empowered by the curriculum to challenge and, possibly, to change it.[6]

It is these suggestions that so enraged Good & Demastes (1995) and led them to accuse advocates of this approach of relativism and of “not taking science seriously”. There are two responses. First, different ways of knowing yield different answers to the same question and, more often, ask different questions. In Pomeroy’s (1996) words, “they are not equal; they are different, and their value is that they provide alternative ways of understanding phenomena. One does not use a hammer to fasten a bolt; the appropriateness of the tool lies in the use to which it is put; equality has nothing to do with it.” Secondly, asking questions about what is distinctive about science and scientific understanding is an essential part of the epistemological understanding necessary for moving freely across borders between sub-cultures. To say that scientific knowledge arises in a particular culture (the Western scientific community) is not to discredit it or to say that it has no currency at all outside that social context, or that it may not (on occasions) be close to a true account of the world. Exposing students from non-Western cultures to the ideas of science or to any other ideas that are from cultures other than their own, providing it is done sensitively, is not to do them a disservice. Quite the contrary; it is a key aspect of their education! Nor is there anything morally repugnant in asserting that traditional knowledge and everyday understanding often fails to stand up to rigorous scientific scrutiny. As Siegel (1997) points out, Western science is ‘biased’ in the sense that it makes epistemological presuppositions that are cultural artefacts, and are not shared by some non-Western cultures, but the bias is only a pernicious one when science is presented as absolute truth or as the only way of knowing. Consideration of traditional knowledge within the science curriculum is not a threat to science, nor is the presentation of scientific knowledge necessarily a threat to traditional knowledge. Within an individual’s personal framework of understanding they can co-exist and can be separately accessed as and when appropriate. The key is a careful consideration of issues located in the history, philosophy and sociology of science.

While I am arguing here for a much more fluid view of what constitutes scientific practice, I recognize that telling students, too early, that scientific inquiry is context-dependent and idiosyncratic could be puzzling, frustrating and even off-putting. This is a similar point to Brush's (1974) concern that teaching the history of science can have an adverse effect on students by undermining their confidence in science. One approach is to take our cue from secondary school chemistry curricula, where we often begin with a very simple representation ("elements are either metals or non-metals"; "bonding is either covalent or electrovalent") and then proceed to qualify these assertions in all manner of ways ("there are varying degrees of metallic/non-metallic character, depending on atomic size and electron configuration"; "there is a range of intermediate bond types, including polarized covalent bonds and lattices involving highly distorted ions, as well as hydrogen bonding, van der Waals forces, etc."). Early in a child's science education, we may find it useful to characterize scientific inquiry as a fairly standard set of steps. Within a simple representation, we can emphasize the importance of making careful observations (using whatever conceptual frameworks are available), taking accurate measurements, systematically controlling variables and so on. As students become more experienced they can be introduced to the variations in approach that are necessary as contexts change – for example, the startlingly different approaches adopted by astronomers and field biologists. Eventually, students can experience for themselves the joys (and frustrations) of having to work out the procedures for themselves. With these experiences comes the realization that doing science successfully involves learning to 'think on one's feet'. In a sense, this progression is similar to those cases in science where scientists begin with a conceptual model (which they know is not 'true') and proceed, through debate and experimentation, to refine and develop it into a more complex theory. The model is merely a device to help them to think more clearly and to gain a measure of predictive control, while the theory is believed to explain the reality they are studying. By analogy, the early childhood version of science can be seen as a *model*, the more sophisticated later version as a *theory* of science and scientific practice.

Once we put people back into science, we open up the possibility that science can be and has been different. Different groups of people have different priorities, they identify different problems, which they approach in different ways, using different theories, instruments and methods. They may even have different criteria of validity and acceptability. If science has different goals, methods and criteria of judgement, it is inevitable that it will generate different knowledge and different theories. This new curriculum message is that science is not propelled exclusively by its own internal logic. Rather, it is shaped by the personal beliefs and political attitudes of its practitioners and reflects, in part, "the history, power structure and political climate of the supportive community" (Dixon, 1973). This can be highlighted by historical studies, by studies of non-Western science, and by studies of the misuse of science for social and political purposes (Hodson, 1993b; Hodson & Dennick, 1994). When reinforced by consideration of some current thinking concerning feminist science and ethno-science, for example, these activities will help to impress on students that we can re-orientate, re-prioritize, and re-direct *our* science and technology towards more socially just and environmentally sound practices.

Correspondence

Derek Hodson, Ontario Institute for Studies in Education, University of Toronto, 252 Bloor Street West, Toronto, Ontario M5S 1V6, Canada.

Notes

[1] Matthews (1992) has documented the extraordinary rise of interest among science educators in the history and philosophy of science during the late 1980s and early 1990s. In addition to the Proceedings of three international conferences at Florida State University, Tallahassee (1989), Queen's University, Kingston (1992) and the University of Minnesota (1995), there have been special issues of a number of journals, including *Educational Philosophy & Theory* (1988), *Synthese* (1989), I*nterchange* (1989, 1993), *Studies in Philosophy and Education* (1990), *Journal of Research in Science Teaching* (1992), *Science Education* (1991) and *International Journal of Science Education* (1990). In 1992, Kluwer launched a specialized journal (*Science & Education*) concerned with historical, philosophical and sociological studies related to issues in science and mathematics education, under the editorship of Michael Matthews.

[2] I am not claiming that all seven myths are promoted by all science curricula. Rather, that most curricula promote one or more of them and that, across the range of curricular provision, all seven are in evidence.

[3] Wellington (1989) provides a range of perspectives on both theoretical and practical issues surrounding the recent resurgence of interest in process-led science teaching in the United Kingdom.

[4] Hodson & Bencze (1998) argue that authentic science includes correlational studies and practical problem-solving, as well as experimental inquiry and theoretical debate. Bencze (1996) outlines the distinctive features of correlational studies; Watts (1991) and Kimbell (1991) are useful sources of information on the teachable features of technological problem-solving.

[5] See Finkel (1992) for a short, but insightful, review of considerations in the sociology of science and Medway (1993) for a clear, concise and provocative discussion of these issues in relation to technology education.

References

Abell, S. K. & Smith, D. C. (1994) What is science? Preservice elementary teachers' conceptions of the nature of science, *International Journal of Science Education*, 16, pp. 475-487.

Abruscato, J. (1988) *Teaching Children Science*. Englewood Cliffs: Prentice Hall.

Bencze, J. L. (1996) Correlational studies in school science: breaking the science-experiment-certainty connection, *School Science Review*, 78(282), pp. 95-101.

Bhaskara Rao, D. (1992) Scientific attitude in secondary school pupils, in S. Hills (Ed.) *The History and Philosophy of Science in Science Education,* Vol. II. Kingston: Queen's University.

Bloor, D. (1976) *Knowledge and Social Imagery*. London: Routledge & Kegan Paul.

Bloor, D. (1991) *Knowledge and Social Imagery*, 2nd edn. Chicago: Chicago University Press.

Brannigan, A. (1981) *The Social Basis for Scientific Discoveries*. Cambridge: Cambridge University Press.

Brush, S. G. (1974) Should the history of science be rated X? *Science*, 183, pp. 1164-1171.

Bryce, T. G. K., McCall, J., MacGregor, J., Robertson, I. J. & Weston, R. A. J. (1987) *TAPS Report of the Project Phase 2 (1983-86)*. Glasgow: Jordanhill College of Education.

Carey, S., Evans, E., Honda, M., Jay, E. & Unger, C. (1989) "An experiment is when you try it and see if it works": a study of grade 7 students' understanding of the contruction of scientific knowledge, *International Journal of Science Education,* 11, pp. 514-529.

Cawthron, E. R. & Rowell, J. A. (1978) Epistemology and science education, *Studies in Science Education*, 5, pp. 31-59.

Chalmers, A. F. (1982) *What is this Thing Called Science?* Milton Keynes: Open University Press.

Collins, H. M. (1991) *Artificial Experts: social knowledge and intelligent machines*. Cambridge: MIT Press.

Collins, H. & Pinch, T. (1982) *Frames of Meaning*. London: Routledge & Kegan Paul.

Collins, H. M. & Pinch, T. (1992) *The Golem: what everyone should know about science*. Cambridge: Cambridge University Press.

Dennick, R. (1992) Analysing multicultural and antiracist education, *School Science Review*, 73(264), pp. 79-88.

Dixon, B. (1973) *What is Science For?* London: Collins.

Duhem, P. (1962) *The Aim and Structure of Physical Theory* (trans. P. P. Weiner). New York: Atheneum Press.

Duschl, R. (1988) Abandoning the scientistic legacy of science education, *Science Education*, 72, pp. 51-62.

Duschl, R. A. (1990) *Restructuring Science Education*. New York: Teachers College Press.

Duveen, J., Scott, L. & Solomon, J. (1993) Pupils' understanding of science: description of experiments or "a passion to explain"? *School Science Review,* 75(271), pp. 19-27.

Feyerabend, P. K. (1962) Explanation, reduction and empiricism, *Minnesota Studies in Philosophy of Science*, 3, pp. 28-97.

Feyerabend, P. K. (1975) *Against Method*. New York: New Left Books.

Finkel, E. (1992) Examining school science: using sociology of science in the study of science classrooms, in S. Hills (Ed.) *History & Philosophy of Science in Science Education*, Vol. 1. Kingston: Queen's University.

Fuller, S. (1988) *Social Epistemology*. Bloomington: Indiana University Press.

Gagne, R. M. (1963) The learning requirements for inquiry, *Journal of Research in Science Teaching*, 1, pp. 144-153.

Gaskell, P. J. (1992) Authentic science and school science, *International Journal of Science Education*, 14, pp. 265-272.

Gauld, C. F. (1982) The scientific attitude and science education: a critical reappraisal, *Science Education*, 66, pp. 109-121.

Geddis, A. N. (1991) Improving the quality of science classroom discourse on controversial issues, *Science Education*, 75, pp. 169-183.

Good, R. & Demastes, S. (1995) The diminished role of nature in postmodern views of science and science education, in F. Finley, D. Allchin, D. Rhees & S. Fifield (Eds) *Proceedings of the Third International History, Philosophy and Science Teaching Conference*, Vol. 1. Minneapolis: University of Minnesota.

Gott, R. & Duggan, S. (1995) *Investigative Work in the Science Curriculum*. Buckingham: Open University Press.

Gott, R. & Duggan, S. (1996) Practical work: its role in the understanding of evidence in science, *International Journal of Science Education*, 18, pp. 791-806.

Haber, L. (1970) *Black Pioneers of Science and Invention*. New York: Harcourt, Brace & World.

Hacking, I. (1983) *Representing and Intervening*. Cambridge: Cambridge University Press.

Hayes, M. (1982) *Starting Primary Science*. London: Edward Arnold.

Hodson, D. (1988) Experiments in science and science teaching, *Educational Philosophy & Theory*, 20, pp. 53-66.

Hodson, D. (1990) Making the implicit explicit: a curriculum planning model for enhancing children's understanding of science, in D. E. Herget (Ed.) *More History and Philosophy of Science in Science Teaching*. Tallahassee: Florida State University.

Hodson, D. (1992) Assessment of practical work: some considerations in philosophy of science, *Science & Education*, 1, pp. 115-144.

Hodson, D. (1993a) Against skills-based testing in science, *Curriculum Studies*, 1, pp. 127-148.

Hodson, D. (1993b) In search of a rationale for multicultural science education, *Science Education*, 77, pp. 685-711.

Hodson, D. (1996) Laboratory work as scientific method: three decades of confusion and distortion, *Journal of Curriculum Studies*, 28, pp. 115-135.

Hodson, D. & Bencze, L. (1998) Becoming critical about practical work: changing views and changing practice through action research, *International Journal of Science Education*, 20, pp. 683-694.

Hodson, D. & Dennick, R. (1994) Anti-racist science education: a special role for the history of science and technology, *School Science & Mathematics*, 94, pp. 255-262.

Hodson, D. & Prophet, B. (1986) A bumpy start to science education, *New Scientist*, 1521, pp. 25-28.

Holton, G. (1978) *The Scientific Imagination: case studies*. Cambridge: Cambridge University Press.

Holton, G. (1986) *The Advancement of Science and its Burdens*. Cambridge: Cambridge University Press.

Holton, G. (1992) How to think about the ‘anti-science’ phenomenon, *Public Understanding of Science*, 1, pp. 103-128.

Kimbell, R. (1991) Tackling technological tasks, in B. E. Woolnough (Ed.) *Practical Science*. Buckingham: Open University Press.

Knorr-Cetina, K. D. (1983) The ethnographic study of scientific work: towards a constructivist interpretation of science, in K. D. Knorr-Cetina & M. Mulkay (Eds) *Science Observed*. London: Sage.

Kumar, A. & Kenealy, P. (1992) An issue of cultural diversity in science, in S. Hills (Ed.) *The History and Philosophy of Science in Science Education*, Vol. II. Kingston: Queen’s University.

Larochelle, M. & Desautels, J. (1991) “Of course, it’s just obvious”: adolescents’ ideas of scientific knowledge, *International Journal of Science Education*, 13, pp. 373-389.

Latour, B. & Woolgar, S. (1979) *Laboratory Life: the social construction of scientific facts*. London: Sage.

Latour, B. & Woolgar, B. (1986) *Laboratory Life: the social construction of scientific facts*, 2nd edn. Princeton: Princeton University Press.

Lave, J. (1988) *Cognition in Practice: mind, mathematics and culture in everyday life*. New York: Cambridge University Press.

Lave, J. (1991) Situating learning in communities of practice, in L. B. Resnick, J. M. Levine & S. D. Teasley (Eds) *Perspectives on Socially Shared Cognition*. Washington: American Psychological Association.

Leach, J., Driver, R., Millar, R. & Scott, P. (1997) A study of progression in learning about ‘the nature of science’: issues of conceptualisation and methodology, *International Journal of Science Education*, 19, pp. 147-166.

Loving, C. C. (1997) From the summit of truth to its slippery slopes: science education’s journey through positivist-postmodern territory, *American Educational Research Journal*, 34, pp. 421-452.

Lubben, F. & Millar, R. (1996) Children’s ideas about the reliability of experimental data, *International Journal of Science Education*, 18, pp. 955-968.

Machwe, P. (1979) *Hinduism: its contribution to science and civilization*. New Delhi: Vikas Publishing House.

Mahoney, M. J. (1979) Psychology of the scientist, *Social Studies of Science*, 9, pp. 349-375.

Martin, B., Kass, H. & Brouwer, W. (1990) Authentic science: a diversity of meanings, *Science Education*, 74, pp. 541-554.

Matthews, M. (1992) History, philosophy and science teaching: the present rapprochement, *Science & Education*, 1, pp. 11-47.

McNairy, M. R. (1985) Sciencing: science education for early childhood, *School Science & Mathematics*, 85, pp. 383-393.

Medway, P. (1993) *Shifting Relations: science, technology and technoscience*. Geelong: Deakin University Press.

Ministry of Education (Ontario) (1987) *Curriculum Guidelines: science. Intermediate and Senior Divisions. Part 1: Program outline and policy*. Toronto: Queen’s Printer for Ontario.

Mitroff, I. I. & Mason, R. O. (1974) On evaluating the scientific contribution of the Apollo missions via information theory: a study of the scientist-scientist relationship, *Management Science: Applications*, 20, pp. 1501-1513.

Mulkay, M. & Gilbert, G. (1984) *Opening Pandora's Box: a sociological analysis of scientists' discourse*. Cambridge: Cambridge University Press.

Nadeau, R. & Desautels, J. (1984) *Epistemology and the Teaching of Science*. Ottawa: Science Council of Canada.

Needham, J. (1954) *Science and Civilization in China* (7 vols). Cambridge: Cambridge University Press.

Needham, J. (1969) *The Grand Titration: science and society in East and West*. London: Allen & Unwin.

Needham, J. (1981) *Science in Traditional China: a comparative perspective*. Hong Kong: Chinese University Press.

Newton-Smith, W. H. (1981) *The Rationality of Science*. London: Routledge & Kegan Paul.

Nott, M. & Wellington, J. (1996) When the black box springs open: practical work in schools and the nature of science, *International Journal of Science Education*, 18, pp. 807-818.

Pomeroy, D. (1996) Science Educators as Cultural Workers: philosophical implications. Paper presented at the 8th IOSTE Symposium, Edmonton.

Qualter, A., Strang, J., Swatton, P. & Taylor, R. (1990) *Exploration: a way of learning science*. Oxford: Basil Blackwell.

Ravetz, J. R. (1971) *Scientific Knowledge and its Social Problems*. Harmondsworth: Penguin.

Reid, D. J. & Hodson, D. (1987) *Science for All: teaching science in the secondary school*. London: Cassell.

Roe, A. (1961) The psychology of the scientist, *Science*, 134, pp. 456-459.

Ryan, A. G. (1987) High school graduates' beliefs about science-technology-society. IV The characteristics of scientists, *Science Education*, 71, pp. 489-510.

Sardar, Z. (1989) *Explorations in Islamic Science*. London: Mansell.

Schibeci, R. A. (1984) Attitudes to science: an update, *Studies in Science Education*, 11, pp. 26-59.

Screen, P. (1988) A case for a process approach: the Warwick experience, *Physics Education*, 23, pp. 146-149.

Siegel, H. (1997) Science Education: multicultural and universal. Paper presented at History and Philosophy of Science and Science Teaching Conference, Calgary.

Slezak, P. (1994) Sociology of scientific knowledge and scientific education: Part 1, *Science & Education*, 3, pp. 265-294.

Smolicz, J. J. & Nunan, E. E. (1975) The philosophical and sociological foundations of science education: the demythologizing of school science, *Studies in Science Education*, 2, pp. 101-143.

Solomon, J., Duveen, J. & Scott, L. (1994) Pupils' images of scientific epistemology, *International Journal of Science Education*, 16, pp. 361-373.

Solomon, J., Scott, L. & Duveen, J. (1996) Large-scale exploration of pupils' understanding of the nature of science, *Science Education*, 80, pp. 493-508.

Tobin, K. G. & Capie, W. (1980) Teaching process skills in the middle school, *School Science & Mathematics*, 80, pp. 590-597.

Traweek, S. (1988) *Beantimes and Lifetimes: the world of high energy physicists*. Cambridge: Harvard University Press.

Watts, D. M. (1991) *The Science of Problem Solving: a practical guide for science teachers*. London: Cassell.

Watts, S. (1986) Biographies of black scientists, in M. Hollins (Ed.) *Science Teaching in a Multi-ethnic Society: issues, practices, resources*. London: ILEA.

Weatherford, J. (1988) *Indian Givers: what the Native Americans gave to the world*. New York: Crown.

Wellington, J. J. (1981) 'What's supposed to happen, Sir?': some problems with discovery learning, *School Science Review*, 63(222), pp. 167-173.

Wellington, J .J. (Ed.) (1989) *Skills and Processes in Science Education*. London: Routledge.

White, F. C. (1983) Knowledge and relativism III: the sciences, *Educational Philosophy & Theory*, 15, pp. 1-29.

Young, R. M. (1987) Racist society, racist science, in D. Gill & L. Levidow (Eds) *Anti-Racist Science Teaching*. London: Free Association Books.