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A Role for History and Philosophy in Science Teaching

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It is 30 years since the last major reforms of science education. Many believe that it is time for reappraisal of these earlier curricula and for the renewal of science education — its content, aims, methods. Also, and importantly, there is renewed interest in the preparation of science teachers. A growing number believe that the history and philosophy of science has an important role to play in this renewal. It is acknowledged by all that there has been far too little interaction and co-operation between philosophers and historians of science and science educators. This is unfortunate because at all levels where there has been co-operation the benefits to science education are apparent, be it in the development of curricula, the production of teaching materials, the writing of textbooks, the conduct of research on science learning, the enhancement of classroom lessons and activities, the preparation of teachers, or the defining of scientific literacy. The present international project, described in my Introduction to this volume, will in some small way further the interaction and co-operation. Given the flight from science classrooms that has occurred, particularly in America, a concerted move to reappraise and improve the situation is timely.

The reforms of the late 1950s and early 1960s had a number of aims, the most important being to create "little scientists" (Roberts, 1982). Learning about science, its history, philosophy, or social context, was a minor consideration. In the States the Russian sputnik inspired the 1958 National Defense Education Bill which put into train a number of new science curricula (Elbers & Duncan, 1959). These are well known by their acronyms — PSSC, CHEM, CBA, BSCS, and ESCP. Over 20 new curricula in maths and science were supported by the National Science Foundation and by 1968 three and a half million students were enrolled in them (Duschl, 1985, p. 547). They were designed largely by academic scientists, with the bright science-orientated student in mind. The 1958 Rockefeller Report on the pursuit of excellence in American education embodies the hopes of the period. At the same time, the Nuffield schemes were introduced in England, and the Messel and ASEP curricula in Australia. Neither the history nor the philosophy of science were much considered in these curricula, although they certainly assumed the then current largely empiricist views on these subjects. This was of course even clearer in the textbooks written to support the curricula.

In most of the curricula the encouraged teaching method was the Bruner-inspired "Inquiry Method." It was recognized that the old didactic methods of instruction were inefficient and counter-productive; few students learned their subject and many deserted science at the first available opportunity. The situation was comparable to that at the turn of the century when one of the first reformers, Henry E. Armstrong, observed,

> I have no hesitation in saying that at the present day the so-called science taught in most schools, especially that which is demanded by examiners, is not only worthless but positively detrimental. (1903, p. 37)

Similar views had been expressed by Ernst Mach, the prominent physicist and philosopher, who was perhaps the first notable scientist to concern himself with issues in science pedagogy. Mach had said,

> I know nothing more terrible than the poor creatures who have learned too much. . . . What they have acquired is a spider's web of thoughts too weak to furnish sure supports, but complicated enough to produce confusion. (Mach, 1895, p. 367).

Against the old didactic methods, the new curricula stressed learning by doing, or science as inquiry. One reviewer of the reforms captured their optimism,

> The PSSC physics curriculum, as with many later NSF-sponsored curricula, was set up in such a way that the student learned by doing experiments, by making his or her own observations, and by generalizing on this first-hand experience. (Crane, 1976, p. 65)

The much published science educator, Joseph Schwab, promoted "science as inquiry" and defended the rationale of the new courses (Schwab, 1962).

With the passage of 30 years, and the benefit of hindsight, some judgments on the reforms can and have been made. The inductivist model of inquiry that they were based upon was known to be deficient, or at least highly controversial, even at the time the curricula were being implemented. Presently the critiques of Kuhn, Popper, Toulmin, Laudan, and others have made untenable some of the central assumptions of the science as inquiry program. The NSF and Nuffield programs assumed that the student came to science as a *tabular rasa*. Such assumptions ought not to be made. Students often have deeply ingrained intuitive beliefs and conceptions regarding natural processes and these affect how the world is seen, how new concepts are understood, and how the student "inquires." Much research has been directed at the Piagetian view that these intuitive beliefs mirror earlier stages in the history of science. For whatever reasons, it is clear that the reforms of the 1960s have run their course. Both students and teachers are leaving the science classroom. One representative review of the reforms has said,

> In spite of new curricula, better trained teachers, and improved facilities and equipment, the optimistic expectations for students becoming inquirers have seldom been fulfilled. (Welch et al., 1981, p. 33)

The same review went on to say,

> The second major reservation teachers expressed about inquiry teaching was that it didn't work for most students. They see it as causing confusion and too difficult for any but the very brightest student.

It is apparent that the curricula and the teaching processes would have benefitted if philosophers and historians had from the outset been more engaged in the reform task.

Some of the problems with the new curricula were identified very early. The British Association for Science Education (ASE) in its *Training of Graduate Science Teachers* stressed the obvious problem of teachers who did not understand, or have an interest in, the nature of science itself. Of graduate teachers it said,

> Many behave and think scientifically as a result of their training but they lack an understanding of the basic nature and aims of science. (Association for Science Education, 1963, p. 13)

The same body in its 1979 report *Alternatives for Science Education* argued for the desirability of a science education for all students to the age of 16. Such a curriculum should "incorporate a reasonable balance between the specialist and generalist aspects of science and should reflect" science as a "cultural activity." In a later report, *Education Through Science* (1980), the teaching of science as a cultural activity was spelt out as

> the more generalized pursuit of scientific knowledge and culture that takes account of the history, philosophy and social implications of scientific activities, and therefore leads to an understanding of the contribution science and technology make to society and the world of ideas.

The ASE has explicitly recognized the importance of the history and philosophy of science in its own *Science in Society* project that includes a reader on the subject (Ramage, 1983).

Manuel, in a comment on the role of philosophy in British science teaching, acknowledged that school science literacy was falling, and appealed for the inclusion of history and philosophy programs in teacher training courses.

> This more philosophical background which is being advocated for teachers would, it is believed, enable them to handle their science teaching in a more informed and versatile manner and to be in a more effective position to help their pupils build up the coherent picture of science — appropriate to age and ability — which is so often lacking. (Manuel, 1981, p. 771)

The current project makes the same appeal.

The flight from science in the USA is dramatic. In 1985–86, 7,100 high schools had no course in physics, 4,200 no chemistry, 1,300 no biology. Between 1971 and 1980, there was a 64 percent decline in the number of undergraduates entering science teaching. It is estimated that 30 percent of science teachers are unqualified to teach the subject. Thirty-five states allow graduation from high school with little or no study of science, a fact reflected in a recent national study that found that 50 percent of 17-year-olds could not find the area of a square given the length of one side. All of this has been documented in much publicized reports, particularly *A Nation At Risk* (Bybee et al., 1984; Dowling & Yager, 1983; National Commission on Excellence in Education, 1983; Weiss, 1978). Not surprisingly in the United States there are many calls for another concerted examination and reform of science education (Bybee, 1977; Bybee et al., 1984; Gallagher & Yager, 1981; Hurd, 1984; National Science Board, 1983; Yager & Penick, 1985).

One indication of American concern with the state of school science teaching is the Carnegie-funded, Stanford-based, national science-teacher testing program. Other indications are the much debated Holmes Group proposals for the reorganization of teacher training and the two Phillips Exeter Academy conferences on Science and Technology Education for Tomorrow's World. Many of these concerns are expressed in the National Science Board's 1983 report *Educating Americans for the 21st Century.*

In England the government's proposal for a national science curriculum has given urgency to the question of what is an appropriate science education (Department of Education and Science, 1985; Thompson, 1987). The Association for Science Education (ASE) has prepared many reports urging the reform and replacement of the still widely used Nuffield school programs. In support of these aims the ASE funded two new curriculum projects, the 1981 Science and Society course and the 1983 Science in its Social Context (SISCON) course. Against the previous positivist stress, the National Secondary Science Curriculum Review in 1983 said that students should gain "some understanding of the historical development of scientific principles and theories." In 1989, three examining bodies are introducing a senior course in the History and Philosophy of Science. All of these developments are as yet on the periphery of school science. Without teachers who have an interest and competence in the history, philosophy, and social studies of science, and without a concerted effort to convince administrators and policy makers of the benefit of such studies, they will remain on the periphery.

Philosophers and historians of science have a valuable role to play in the reform of science education; their collaboration with science educators has been too infrequent.

History of Science and the Curricula

Historians of science have been more active than philosophers in educational endeavours. Both the American and the British History of Science Associations have education subcommittees. The British Association was founded in 1946 and immediately began collaboration with the then Science Masters' Association and the Association of Women Science Teachers (the forerunners of the ASE) on how the history of science might be better incorporated into school courses. Much earlier, in 1917, the British Association for the Advancement of Science (BAAS) had urged the historical approach to science teaching, saying that the history of science was a "solvent that dissolved the artifical barriers between literacy studies and science that the school timetable sets up" (1917, p. 140). In the following year the J. J. Thompson Report endorsed these claims (Waring, 1979).

The American History of Science Society is involved with the National Commission on Social Studies and the American Association for the Advancement of Science in curricula reform projects. The latter organization is sponsoring a Liberal Education and the Sciences project. Much of this effort is directed at the history syllabus, trying to increase its coverage of scientific and technological developments.

On the continent at the end of the 19th century, Ernst Mach was advocating a philosophical and historical approach to the teaching of school science; this in his influential lecture to school teachers, "On Instruction in the Classics and the Sciences" (Mach, 1895). At the same time Pierre Duhem was urging the historical method in the teaching of physics. He was perhaps the first to draw the analogy between the development of science and the growth of individual understanding (a view later developed by Piaget in his genetic psychology). Duhem was sensitive to the problems of science teaching. He said that the tension between the logic of the subject and the psychology of the student "make the teaching of this science particularly delicate" (Duhem, 1954, p. 258). His recommendation was that

> the legitimate, sure, and fruitful method of preparing a student to receive a physical hypothesis is the historical method. To retrace the transformations through which the empirical matter accrued while the theoretical form was first sketched; to describe the long collaboration by means of which common sense and deductive logic analyzed this matter and modelled that form until one was exactly adapted to the other: that is the best way, surely even the only way, to give to those studying physics a correct and clear view of the very complex and living organisation of this science. (Duhem, 1954, p. 268)

There has been a small number of important, historically informed science curricula developed. In America this collaboration between historians and educators has been particularly productive at Harvard University. James Bryant Conant, the university president and physicist-historian, wrote popular books arguing for a historical approach to science pedagogy. He also prepared the influential *Case Studies in Experimental Science* (Conant, 1964). Thomas Kuhn, the most widely read philosopher of science in the last three decades, has said that Conant "first persuaded me that historical study could yield a new sort of understanding of the structure and function of scientific research" (Kuhn, 1977, p. xi). Another Harvard physicist to understand his discipline in historical terms was Gerald Holton who in the early 1960s collaborated with science educators to produce the Harvard Project Physics Course (see Holton, 1978). Holton was a member of the National Commission on Excellence in Education that produced *A Nation At Risk*, and has commented upon its implications for science education (Holton, 1986).

Harvard Project Physics has been an exemplar of what the history of science can contribute to the development of science curricula. The success of the course is encouraging for the curricula endeavours that are advocated here; likewise, there are lessons to be learnt from its deficiencies (Brush, 1987; Holton, 1978; Russell, 1981). It was the only one of the new courses to give serious consideration to the history and cultural context of science. In the mid-1970s, 15 percent of students taking physics courses in America took the Project Physics Course. These students learned not to think in terms of a standardized "scientific method" but gained an appreciation of the roles of diverse approaches, imagination, confirmation, and instrumentation in the pursuit of scientific knowledge (Aikenhead, 1974). Further, their knowledge of the discipline did not suffer in virtue of this appreciation (Brush, 1987, p. 78).

One matter highlighted in the Project Physics reviews is the important role of the teacher in the effectiveness of the program. Wayne Welch claims that most research studies indicate that no more than 5 percent of the variance in student learning is due to the curriculum; most is due to the teacher (Welch, 1979). This is one reason why Americans try to develop "teacher proof" programs. Another approach is to ensure that teachers have a good grounding in the history and philosophy of science and then let their own enthusiasm and competence do the rest.

The Biological Science Curriculum Study (BSCS), introduced in the early 1960s and adapted in many countries including Israel and Australia, was an example of a historically informed curriculum. Joseph Schwab was involved in its development. "Science as Inquiry" was its motto. For Schwab,

> the essence of teaching of science as enquiry would be to show some of the conclusions of science in the framework of the way they arise and are tested. (Schwab, 1962, p. 40)

The benefits of a historical approach to the teaching of school science have been well canvassed, the most often alluded to being its ability to bridge the "two cultures" dramatically portrayed by C. P. Snow. Research on curricula, student performance, and attitudes has established other positive results including increased understanding of science, increased interest in the subject, enhanced critical thinking, and increased retention of girls in school science programs (Brush, 1974, 1987; Finocchiaro et al., 1980; Klopfer, 1969; Kauffman, 1979; Russell, 1981; Sherratt, 1982). History and philosophy give a human face to science, and go some way to overcoming its scientistic image (Brush, 1978; Omerod 1971).

In a discordant view, Thomas Kuhn argued that for school children the proper teaching of the history of science was corrosive of "normal" science learning. He felt that in a science classroom the history of science should be distorted, that earlier scientists should be represented as having worked upon the "same set of fixed problems" as modern scientists (Kuhn, 1970, p. 138). Given that the subject matter of science is complex, there seems little reason why the classroom history of science cannot be correspondingly complex. Karl Popper said of Kuhn's normal scientist that he has been badly taught, that he has technique without understanding.

It is worth stressing that the main argument for the history of science in science education is that it promotes better science learning. This is the point made repeatedly by Ernst Mach one century ago. He said then that

> whoever knows only one view or one form of a view does not believe that another has ever stood in its place, or that another will ever succeed it; he neither doubts nor tests. (Mach, 1911, p. 17)

History of Science and the Psychology of Learning

Jean Piaget, following Duhem, formulated the notion that in cognitive development ontogeny recapitulates phylogeny.

> The fundamental hypothesis of genetic epistemology is that there is a parallelism between the progress made in logical and rational organisation of knowledge [history of science] and the corresponding formative psychological processes [individual development]. (Piaget, 1970, p. 13)

This claim of Piaget's has been the basis of an influential research program. Thomas Kuhn said of Piaget that, "part of what I know about how to ask questions of dead scientists has been learned by examining Piaget's interrogations of living children" (Kuhn, 1977, p. 21). Conversely, the historian of science, Alexandre Koyre, observed that it was Aristotle's physics that taught him to understand Piaget's children. This side of Piaget's claim has great importance for science teaching; the past of science can illuminate the present of science learning.

Similar views had earlier been elaborated by philosophers of education such as Richard Gregory and Percy Nunn. Under their influence there was a sustained interest in the history of science in British secondary science teaching in the 1920s and 1930s (Brock, 1987). F. W. Sanderson, the Headmaster of Oundle School from 1892 to 1922, championed the reading of primary sources and the portrayal of science as an integral part of the development of culture. His advice to students was to

> Read Archimedes. . . . Read Faraday's papers . . . mark the long processes of experiments . . . the diversity of methods, the trials and failures, uncertainties, doubts and suggestiveness, the atmosphere of discovery. (Sherratt 1982, p. 232)

The mixed history of "discovery learning" in science education can illuminate the Piagetian claim (Atkinson & Delamont, 1977; Hodson, 1987). The Nuffield schemes for instance urged that children become "scientists for a day." What this actually meant was supposedly unproblematic; teachers were to guide the children in their scientific discoveries. It is a commonplace among teachers that when children are guided to discover some conceptualization, relationship, or law about the phenomena they are presented with, they often come up with ideas that are strikingly like those that have at different times been dominant in the history of the relevant science. This recapitulation effect has been extensively researched.

Rosalind Driver has found that children have an organic view of combustion, that they see burning as the liberation of something firey which leaves an ash (Driver et al., 1985, p. 158). Bartov has shown that intuitive conceptions of biological processes are highly teleological. As might be expected initial understandings of evolution are very Lamarckian (Brumby, 1979; Lucas, 1971). There is an extensive literature demonstrating the fundamentally Aristotelian nature of intuitive ideas in mechanics (Champagne et al., 1980; DiSessa, 1982; McCloskey, 1983; Whitaker, 1983). These relationships have been demonstrated across the scientific spectrum. They have been the subject of scores of papers at two international conferences "Misconceptions in Science Learning" (Helm & Novak, 1983; Novak, 1987).

History of science, learning theory, and pedagogy come together in the science classroom. How children intuitively understand processes will affect how they assimilate new ideas. This is a simple enough point, one that was driven home in the learning theories of David Ausubel and Jerome Bruner. Ausubel in his major work *Educational Psychology: A Cognitive View* stated that

> if I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.

Understanding the obstacles to development in the history of science can in some measure throw light on problems in individual learning. No one is suggesting an identity of individual and historical learning, or that Aristotelian physics or phlogiston chemistry is child's play. What is being suggested is that the history of science enables us to better understand what current conceptions are and that knowledge of "epistemological obstacles" in the development of science can illuminate similar problems in individual learning. Appreciating where great minds had difficulty attunes a teacher to where lesser minds might also have difficulty. Hogg, in a now dated, historically based chemistry text, expressed the matter well:

> The historic development is a logical approach. The slow progress of the early centuries was owing to a lack of knowledge, to poor technique and to unmethodical attack. But these are precisely the difficulties of the beginner in chemistry. There is a bond of sympathy between the beginner and the pioneer. (Hogg, 1938, p. vii)

There is of course a danger of simplistic history, or of Whiggish history, being taught, though with the proper preparation of teachers this should be no more a worry than simplistic mechanics being taught. The reverse danger is to let the best get in the way of the better. Clearly there is no single "history of science," and it is a mistake to pretend that there is. The divisions between internalists and externalists, rationalists and irrationalists, remain fairly clear. The relative importance given to experiment and reason in Galileo's mechanics is, for instance, still debated. But this should not be a cause for embarrassment. Teachers teach best when they provide not answers but questions that engage and stimulate the student. History taught well can do this. Albert Einstein remarked that it was the reading of Ernst Mach's historical work *The Science of Mechanics* (1883) that freed his mind to contemplate new interpretive frameworks for mechanics. Of his own education Einstein said,

> After I passed the final examination, I found the consideration of any scientific problems distasteful to me for an entire year. . . . It is, in fact, nothing short of a miracle that the modern methods of instruction have not entirely strangled the holy curiosity of inquiry. (Schilpp, 1951, p. 17)

This historical dimension can help us understand the robustness of intuitive beliefs. McCloskey found that 93 percent of high school physics students prior to taking a physics course believed an impetus-like quality was acquired by an object when it was set in motion, and that this "impetus" maintained the motion. Hardly surprising. He also found that 80 percent still had the belief after successful completion of the course! He remarked,

> The misconception appears to be grounded in a systematic intuitive theory of motion that is inconsistent with the fundamental principles of Newtonian mechanics. . . . The intuitive theory bears a striking resemblance to the pre-Newtonian theory of impetus. (McCloskey, 1983, p. 122)

Many others have remarked on this failure of science teaching to disturb ingrained beliefs (Archenhold et al., 1980; Brumby, 1979; Champagne et al., 1980; Gilbert et al., 1982; Viennot, 1979). Students often live in two worlds, one for the science exam, another for everyday life. This is alarmingly illustrated in recent American surveys showing that belief in astrology is very little affected by completion of an American science degree. The history of science reminds us of the difficulty there is in learning and grasping even very simple notions. Pierre Duhem, in his warnings against grounding science instruction in common sense, had at the turn of the century observed,

> Now is it clear merely in the light of common sense that a body in the absence of any force acting on it moves perpetually in a straight line with constant speed? Or that a body subject to a constant weight constantly accelerates the velocity of its fall? On the contrary, such opinions are remarkably far from common-sense knowledge; in order to give birth to them, it has taken the accumulated efforts of all the geniuses who for two thousand years have dealt with dynamics. (Duhem, 1954, p. 263)

The rise of constructivism in educational psychology has led to a greater appreciation of the place of history and philosophy of science in the practice and theory of science education. Constructivism is a Piaget-inspired variant of cognitive learning theory. Joseph Novak in science education and Ernst von Glasersfeld in mathematics education are two representative exponents of the position (Novak, 1987; Glasersfeld, 1987). It is an anti-empiricist, anti-behaviourist learning theory. It draws heavily on the "framework" theorists in philosophy of science — Kuhn, Toulmin, Bachelard. Given this, it is not surprising that epistemological issues are a commonplace in constructivism. The acknowledged importance of epistemology for constructivism can be seen in the Introduction to the major bibliography of research in the field. There Duit says,

> The label "alternative framework" used in the title of the bibliography stands for a program accepted by the overwhelming majority of researchers in our field. This is a program which views students' conceptions as conceptions in their own right and not as false ideas which have to be erased as fast as possible. (Pfundt & Duit, 1988, p. xxxv)

This follows the introduction of the expression "student's alternative frameworks" in the Driver and Easley (1978) review.

It is easy to see how constructivism is so dependent on positions in the history and philosophy of science, and how such positions can contribute to the critical exposition of the program. Issues of truth, realism, and rationality are explicit in constructivist debate. How can knowledge of the process of conceptual change in the history of science inform, and be informed by, the processes of individual conceptual change; and further, what epistemological issues are entailed by both? Karl Popper for instance makes a clear distinction between second world, experiential events and third world, scientific theories. This is his "science without a knowing subject." Constructivism bridges these worlds, but the bridge requires epistemological support.

Philosophy and Science Teaching

In science education the effects of philosophical understandings or misunderstandings are everywhere apparent — from statements of putative scientific method, to accounts of scientific law, to opinions about the structure of science. Yet philosophers have only rarely concerned themselves with issues in science education, a matter lamented by Robinson (1969), Ennis (1979), and Martin (1974) in their benchmark reviews of the literature. This neglect is in marked contrast to the expanding studies in philosophy of science itself. Many have called for the increased involvement of philosophers of science in science education (Harms & Yager, 1981; Koertge, 1969; Summers, 1982) but with some exceptions (such as Israel Scheffler and Michael Martin) these calls have been unheeded. Joseph Agassi is another. His dialogue-form history of physics (between himself and his son) is a wonderful example of how a philosopher/historian can enrich science instruction (Agassi, 1968).

Philosophy enhances classroom teaching. A simple lesson on mechanics can be transformed if questions are raised about the relationship of theories to evidence, about what is required of a good experiment, or why for example we define acceleration as change of velocity with respect to time rather than distance. Lessons on evolution are more engaging if questions about the appropriate domains of science and religion are raised or if questions about the reality or conventionality of species are investigated (an issue very important in the reception of Darwinism). Children can be introduced to the metaphysical issue of Darwin's naturalism and its ramifications for understanding man's place in nature. Issues can be raised about how Darwin's theory was created and the adequacy of the then contemporary evidence. Attention might be drawn to the apparent circularity of the law of survival of the fittest; or of the repeated claims for gradualism despite all evidence being against it. In all of these ways, historical and philosophical perspectives can be developed, and they can contribute to the better and more interesting teaching of science.

Lessons on atomic structure can provide the opportunity for the discussion of models in science, and of the central issue of how evidence relates to theory, and of the grounds for theory choice. The basic issues of realism and instrumentalism can in some appropriate manner be raised. Students traditionally learn the "billiard ball" model, the "plum pudding" model, the "solar system" model. This passing parade has more interest and intellectual bite if some elementary questions about models and the world are asked: Are they pictures of the world? Are statements about them true or just useful? What makes a statement true? Osiander's famous instrumentalist preface to Copernicus' *On the Revolutions of the Heavenly Spheres* could be an appropriate place to start such discussion. There has been discussion of these matters in the science education literature (Hodson, 1982; Lind, 1980; Ormell, 1980; Osborne & Gilbert, 1980).

The teaching of combustion can include an appreciation of phlogiston theory. When understood historically it is clear that it was not the silly theory that it is often made out to be. Students can be asked what its strengths were, how much it was in accord with observation, and why the phlogiston theory was held by scientists of the greatest regard — all matters that raise interesting questions about the process of scientific change and the evaluation of theories. Just such an extended unit of work has been trialled in some English schools. This is the type of co-operation between historians and educationalists that is required (Pumfrey, 1987).

A simple lesson on the pendulum can be enhanced if historical matters about Galileo and his disputes with his Aristotelian opponents are introduced — the crucial issue of the pendulum law being "true" only for "ideal" pendula, the importance of "other things being equal" clauses in the statement of scientific law, and the connections between mathematical descriptions and physical reality. These were central issues in the Scientific Revolution. They are illustrated in the history of the physics of pendulum motion. Galileo said of heavy and light pendula (iron and cork) that when set swinging they will remain in synchrony for a "thousand oscillations." When students do the experiment, the pendula are out of synchrony within two dozen swings, a matter confirmed in replications of Galileo's experiment (Naylor, 1974). What does this tell us about Galileo, about the relationship of evidence to theory in science, about the interpretation of experiment, about the role of rhetoric in science? Hovering over all of these issues is the fundamental one of the mathematization of science, and the connection between mathematical formulae and events in the world (Matthews, 1987). Students can only gain by being exposed to these issues, and by being encouraged to think them through.

There is no subject matter that cannot be made more interesting and engaging by the introduction of philosophical considerations, be they world view considerations or technical, analytic ones. The object is not to teach the philosophy, but to enhance the learning and to promote a greater awareness of the intellectual excitement and achievement of science; to see it as a cultural activity that informs other areas of life (religion, ethics, philosophy) and is in turn informed and influenced by them; to begin to understand how, and in what sense, science gives us the best understanding we have of the world we live in.

There are many rich fields in philosophy of science that have a relevance to science education. There is a recent and growing literature on girls and school science, as evidenced in the 1987 special issue of the *International Journal of Science Education.* Independent of this there has been a lively debate in philosophy of science over feminism and epistemology, and over the sexist assumptions in methodology and the history of science. Clearly the two strands can only benefit from interaction.

The philosophy of mathematics is another field that can contribute to science education. It is clear that modern science is mathematical. It is also clear that inadequate mathematics is one of the major obstacles to the growth of scientific understanding. There has been a great deal of work done on the historical development of mathematics and its associated philosophical problems. The contribution of Imre Lakatos is perhaps the best known (Lakatos, 1977). Mathematics educators have paid attention to this corpus, and under the influence of constructivism they have utilized it in studies of the psychology of mathematics and in the development of curricula and teaching methods (Glasersfeld, 1988; Sinclair, 1987). Despite mathematics being so central to science, science education has paid little attention to this scholarship in mathematics education and in the philosophy of mathematics. Once more there can only be benefits from collaboration. The same can be said of the research in cognitive science.

The benefits of science teachers having an interest and competence in the history and philosophy of science are apparent. What is required is much greater collaboration between historians, philosophers, and science educators in the training of teachers, the preparation of classroom materials, the conduct of research, and the analysis of textbooks and programs. To some extent this has happened in the past; there are encouraging signs that it will be more common in the future.

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