Findings generated by recent research in science education, international debate on the guiding purposes of science education and the nature of scientific and technological literacy, official and semi-official reports on science education (including recommendations from prestigious organizations such as AAAS and UNESCO), and concerns expressed by scientists, environmentalists, and engineers about current science education provision and the continuing low levels of scientific attainment among the general population, have led to some radical re-thinking of the nature of the science curriculum. There has been a marked shift of rhetorical emphasis in the direction of considerations of the nature of science, model-based reasoning, inquiry-based learning, scientific argumentation and the use of language-rich learning experiences (reading, writing, talking) to enhance concept acquisition and development. These findings, arguments and pronouncements seem to point very clearly in the direction of regarding science education as a study of scientific practice. This book presents a comprehensive, research-based account of how such a vision could be assembled into a coherent curriculum and presented to students in ways that are meaningful, motivating and successful. The author takes what might be described as an anthropological approach in which scientists are studied as a socially, economically and politically important community of people. This group has its own distinctive language, body of knowledge, investigative methods, history, traditions, norms and values, each of which can be studied explicitly, systematically and reflectively. This particular approach was chosen for the powerful theoretical overview it provides and for its motivational value, especially for students from sociocultural groups currently under-served by science education and under-represented in science.

The book, which is both timely and important, is written for teachers, student teachers, graduate students in education, teacher educators, curriculum developers and those responsible for educational policy. It has the potential to impact very substantially on both pre-service and in-service science teacher education programmes and to shift school science education practice strongly in the direction currently being advocated by prominent science educators.

The author is Emeritus Professor of Science Education at the Ontario Institute for Studies in Education, Adjunct Professor of Science Education at the University of Auckland, and Visiting Professor at the University of Hong Kong. His major research interests include: history, philosophy & sociology of science and its implications for science education; STSE education and the politicization of science education; science curriculum history; multicultural and anti-racist education; and science teacher education via action research.
TEACHING AND LEARNING ABOUT SCIENCE
Teaching and Learning about Science
Language, Theories, Methods, History,
Traditions and Values

By

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A C.I.P. record for this book is available from the Library of Congress.

ISBN 978-94-6091-051-7 (paperback)

Published by: Sense Publishers,
P.O. Box 21858, 3001 AW Rotterdam, The Netherlands
http://www.sensepublishers.com

Printed on acid-free paper

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To Susie – for making it all worthwhile
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In a previous book, *Towards Scientific Literacy: A Teachers’ Guide to the History, Philosophy and Sociology of Science* (Hodson, 2008), I presented a critical reading of the vast and complex literature encompassing the history of science, philosophy of science and sociology of science (HPS). The prime purpose of that book was to identify some key ideas in HPS for inclusion in the school science curriculum, in line with the prominence given to HPS in recent international debate in science education and the numerous influential reports on science education that identify the centrality of HPS to scientific literacy. This book discusses how that particular selection of HPS ideas can be assembled into a coherent curriculum and presented to students in ways that are meaningful, motivating and successful.

I am categorically not arguing for a formal course in history, philosophy and sociology of science. In its undiluted form, HPS is too demanding for most school age students. More importantly, it is too dry and dusty to be of sufficient interest to more than a handful of students. Instead, I take what might be described as an anthropological approach in which scientists are studied as a group of people with considerable social, economic and political importance in our society, a group that has its own distinctive language, body of knowledge, investigative methods, history, traditions, norms and values. This approach is chosen both for the theoretical overview it provides and for its motivational value, especially for students from sociocultural groups currently under-served by science education and under-represented in science.

Over the past two decades, findings from science education research, international debate on the guiding purposes of science education and the nature of scientific and technological literacy, official and semi-official reports on science education (including recommendations from prestigious organizations such as AAAS and UNESCO) and concerns expressed by scientists, environmentalists and engineers about current science education provision and the continuing low levels of scientific attainment among the general population, have led to some radical re-thinking of the nature of the science curriculum. There has been a marked shift of rhetorical emphasis in the direction of: (i) considerations of the nature of science, (ii) model-based reasoning, (iii) inquiry-based learning, (iv) scientific argumentation, and (v) use of language-rich learning experiences (reading, writing, talking) to enhance concept acquisition and development. Two years ago, a major report on future directions for science education published by the US-based
National Research Council (Duschl, et al., 2007) stated: “students who understand science: (a) know, use and interpret scientific explanations of the natural world; (b) generate and evaluate scientific evidence and explanations; (c) understand the nature and development of scientific knowledge; (d) participate productively in scientific practices and discourse” (p. 334). These findings, arguments and pronouncements seem to point very clearly in the direction of regarding science education as a study of scientific practice, rather than the traditional emphases on acquisition of content and understanding of “the scientific method” (in its narrow sense). This book is an attempt to present a comprehensive, research-based account of how such a vision could be translated into curriculum practice. It is written as a contribution to critical consideration of the curriculum image of science, scientists and scientific practice, and the values that underpin it, seeking change wherever deemed necessary, and thereby exerting pressure for change on science itself.

Chapter 1 identifies the key role of HPS in achieving critical scientific literacy. Chapter 2 surveys the research literature concerning students’ understanding of HPS issues. Chapter 3 surveys the parallel research literature focused on teachers’ understanding of HPS issues and the ways in which that understanding influences their curriculum decision-making and, in turn, impacts students’ HPS understanding. Chapter 4 introduces the anthropological approach to teaching and learning about science – in particular, King and Brownell’s (1966) argument that the academic disciplines (including science) can be considered in terms of eight primary characteristics: a community, an expression of human imagination, a domain, a tradition, a syntactical structure (a distinctive mode of inquiry and cluster of methods for generating and validating new knowledge), a substantive structure (a complex framework of concepts, propositions, laws, models and theories), a specialized language, and a valuative and affective stance. Each of these characteristics is considered in Chapters 4 to 10, though discussion of some characteristics extends over more than one chapter. For example, history of science (science as a tradition) is prominent in Chapters 4, 5, 6, 7, 8 and 10. In addition to introducing the anthropological approach, Chapter 4 addresses the notion of science as a community of practice, addresses some important demarcation issues, and considers error, bias and misconduct in science. Chapter 5 presents further thoughts on demarcation in relation to pseudosciences, traditional knowledge, technology, and what Layton et al. (1993) refer to as “practical knowledge for action”. Chapter 6 focuses on the substantive structure of science; Chapter 7 concerns the syntactical structure of science. Chapter 8 addresses some key issues relating to the distinctive language of science; Chapter 9 focuses on the use of language-rich curriculum experiences (talking, reading, writing and listening) in assisting students to acquire and develop conceptual understanding and enhance their understanding of HPS issues. Chapter 10 considers science as a historical tradition, the distinctive values of science, and the driving forces of contemporary scientific practice. The chapter ends by posing a question about whether these underlying values can and should be changed.
The book can be read in a number of ways. Some readers might prefer to read Chapters 2 and 3 after Chapters 4 to 10, on the grounds that interpretation of research findings relating to students’ and teachers’ HPS understanding is easier in the light of prior discussion of the eight disciplinary characteristics. My own view is that Chapters 2 and 3 provide important pointers to the kind of approach that teachers can and should be using in teaching about science, scientists and scientific practice, and so they are better located early in the book. Chapters 6, 7, 8 and 10 can be read in any order. The nature of scientific knowledge, the investigative methods of science and the language of science are closely intertwined and discussion of any one aspect is considerably enhanced by discussion of the others. It is also enhanced by an appreciation of the history, traditions, norms and underlying values of science. Numerous cross-references are included to assist readers make these connections. Because the theoretical concerns and pedagogical strategies discussed in Chapter 9 have direct relevance to matters addressed in Chapters 6, 7, 8 and 10, some readers might prefer to read this chapter immediately after Chapter 6 or Chapter 7, or even leave it until they have read Chapter 10.

The book represents my thoughts about science and science education following a career extending over more than forty years. My thinking has been informed by experiences as a researcher in synthetic organic chemistry, a science teacher in four schools, and a university-based science educator in five universities, extending over four countries. It has been enriched by countless discussions with students, colleagues and friends. My intention has been to provide a resource to stimulate further debate about the many ways in which considerations in HPS impact science education. More provocatively, how such debate might change the science education we provide and the science in which we engage.

Derek Hodson
Auckland
May, 2009
ACKNOWLEDGEMENTS

This book could not have been written without the unwavering love, inspiration, encouragement and support of my wife, Sue Hodson. To you, Susie, I extend my heartfelt thanks. I also thank the numerous colleagues and students at the Ontario Institute for Studies in Education, University of Hong Kong and University of Auckland for enriching my thinking and stimulating my imagination through many discussions of science education issues extending over many years.

I also extend my thanks to Professor Richard Duschl, the Open University, Taylor and Francis and John Wiley & Sons Inc. for permission to reproduce figures and tables originally published elsewhere.


- Figure 6.1 is reproduced with permission of John Wiley & Sons Inc. Source: Driver, R., Newton, P. & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. Science Education, 84(3), 287–312 (Figure 1, p. 296) Copyright 2000. These authors had adapted a figure previously published in: R.N. Giere (1997). Understanding Scientific Reasoning. 3rd edition. Fort Worth, TX: Holt, Rinehart & Winston.


- Figure 8.1 is reproduced with permission from Taylor and Francis (http://www.informaworld.com) Source: Simon, S., Erduran, S. & Osborne, J. (2006). Learning to teach argumentation: Research and development in the science classroom. International Journal of Science Education, 28(2–3), 235–260 (Figure 1, p. 240).
CHAPTER 1
SCIENTIFIC LITERACY AND THE KEY ROLE OF HPS

Some 20+ years ago, Ezra Shahn (1988) declared that scientific illiteracy is a serious and persistent problem. At one level it affects nations; because large parts of their populations are not adequately prepared, they cannot train enough technically proficient people to satisfy their economic and defense needs. More basically it affects people; those who are science illiterate are often deprived of the ability to understand the increasingly technological world, to make informed decisions regarding their health and their environment, to choose careers in remunerative technological fields and, in many ways, to think clearly. (p. 42)

This passage raises important questions about the kind of scientific and technological knowledge we should include in the curriculum and about the levels of attainment in acquisition of that knowledge we should be seeking. It highlights the key distinction between an education that prepares students for a career as a professional scientist, engineer or technician and an education that focuses on wider citizenship goals. It also prompts questions such as “Who benefits from increased levels of scientific literacy?” and “What is science education for?” Inevitably, different answers to these questions are given by different stakeholders in the science education enterprise: students, teachers, parents, scientists, politicians, employer groups, groups of “concerned citizens”, science education researchers, science teacher educators, science curriculum developers, and all the other groups and institutions with an interest in science and technology education. What emerges by way of science curriculum at any particular time is the outcome of argument, negotiation and compromise among these groups, some of whom wield more power than others. For convenience, and following the suggestion of Thomas and Durant (1987), arguments for raising general levels of scientific and technological literacy, sometimes expressed in terms of enhancing public understanding of science and technology, can be categorized into perceived benefits to science, benefits to individuals and benefits to society as a whole.

Benefits to science are seen largely in terms of increased numbers of recruits to science-based professions (including medicine and engineering), greater support for scientific, technological and medical research, and more realistic public expectations of science. Little by way of elaboration needs to be said about the first argument, save that increased recruitment might also result in increased diversity within the community of scientists. Increased numbers of women and members of
eth­nic mino­rity groups, cur­rently under­re­presented in sci­ence and tech­no­logy in many coun­tries, would do much to en­rich the sci­ence­based pro­fes­sions and might ser­ve to re­di­rect and reor­ient prior­i­ties for re­search and de­vel­op­ment – a mat­ter that will be ad­dress­ed, albeit brief­ly, lat­er in the book. With regard to the other per­ceived ben­efits for sci­ence, it could be argued that con­fi­dence in sci­entists, con­tinu­ing pub­lic sup­port for sci­ence, and the high lev­els of pub­lic fund­ing sci­ence cur­rently enjoys, de­pend on cit­i­zens hav­ing some gen­eral un­der­stand­ing of what sci­entists do and how they do it. More sig­nifi­cantly, per­haps, sup­port de­pends on whether the pub­lic val­ues what sci­entists do. Re­search by Miller (2004) sug­gests that the over­whelm­ing ma­jority of cit­i­zens (at least in the Unit­ed States) are sup­port­ive of cur­rent lev­els of fund­ing for sci­entific re­search and con­sider that this re­search has con­trib­uted sub­stan­tially to rais­ing both the stand­ard and the qual­ity of life. For many years there ap­peared to be no cause for the sci­entific estab­lish­ment to be con­cerned about lack of sup­port for re­search in fields such as ma­ter­i­als sci­ence, biolog­i­cal sci­ences and medi­ce; whatever pub­lic doubts ex­isted tended to fo­cus on mor­al­eth­i­cal is­sues raised by de­vel­op­ments in such fields as stem cell re­search, gen­et­ic man­i­pula­tion and xenotransplant­ation, and oc­cas­ional con­cern about the thor­ough­ness and de­pend­abil­ity of drug test­ing pro­to­cols. As Giddens (1991) ob­scoped, “lay at­titudes to­wards sci­ence, tech­no­logy and oth­er esoteric forms of ex­pert­ise . . . tend to ex­press the same mixed at­titudes of rever­ence and re­serve, ap­proval and dis­quiet, enthu­si­asm and ap­athy, which phi­losophers and so­cial anal­ysts (themselves ex­pert­s of sorts) ex­press in their writ­ings” (p. 7). How­ever, it is prob­a­bly true to say that there has been a sig­nif­i­cant de­cline in pub­lic con­fi­dence in sci­ence and sci­entists in re­cent years as a con­se­quence of the BSE epi­sode (the so-called “mad cow dis­ease”) in the Unit­ed King­dom and con­cerns about bird flu, SARS, West Nile Virus and oth­er trans­mis­sible dis­eases – fuelled by the wild swings be­tween panic and com­pla­cency in the news me­dia. Skep­tic­ism is now rife re­gard­ing the bland as­sur­ances about health risks as­soci­ated with nu­clear pow­er sta­tions, over­head pow­er lines and mo­bile phones; there is un­ease about the emer­gence of so-called “super­bugs” in hospi­tals, anxi­ety about the envi­ron­men­tal im­pact of genet­i­cally engineered crops and, un­til the last year or so, se­ri­ous con­cern about the fail­ure of sci­entists to reach con­sen­sus about the causes, sig­nif­i­cance and pro­per re­sponse to global warm­ing and cli­mate change. It is worth not­ing, with regard to such mat­ters, that pub­lic per­cep­tion of sci­ence and sci­entists is im­pacted asym­metri­cally: epi­sodes that wor­ry the pub­lic and threat­en trust in sci­ence always seem more viv­id, com­pelling and mem­o­rable than events likely to gen­er­ate ap­proval and sup­port. Pub­lic­ity about the harm­ful side ef­fects of in­se­c­ti­cide use, for ex­am­ple, is li­kely to be more in­flu­en­tial on pub­lic opin­ion than re­ports about the de­vel­op­ment of a new high yield food crop. Among some sec­tions of the pub­lic there is mount­ing con­cern about the in­creas­ing do­mi­na­tion of sci­en­tific and tech­no­log­i­cal re­search by com­mer­cial, gov­ern­men­tal and mil­i­tary in­terests, the in­creas­ing vul­ner­a­bil­ity of sci­ence and sci­entists to the pres­sures of cap­i­tal­ism and pol­i­tics, and the in­creased se­crecy and vested in­ter­est that re­sult. As Baskaran and Boden (2006) com­ment, West­ern sci­ence seems to have moved from be­ing “an ac­tiv­ity com­mitted to the pro­duction of pub­lic goods for public
benefit to the producer of private goods primarily for commercial (profitable) exploitation” (p. 43). The close link between science and commerce in the field of genetic engineering has been a particular trigger for deepening mistrust of scientists. Indeed, Ho (1997) claims that “practically all established molecular geneticists have some direct or indirect connection with industry, which will set limits on what the scientists can and will do research on . . . compromising their integrity as independent scientists” (p. 155). In consequence, as Barad (2000) notes, “the public senses that scientists are not owning up to their biases, commitments, assumptions, and presuppositions, or to base human weaknesses such as the drive for wealth, fame, tenure, or other forms of power” (p. 229). In its third report, the (UK) House of Lords Select Committee on Science and Technology commented on what it perceives as a “crisis of trust”:

Society’s relationship with science is in a critical phase . . . On the one hand, there has never been a time when the issues involving science were more exciting, the public more interested, or the opportunities more apparent. On the other hand, public confidence in scientific advice to Government has been rocked by a series of events, culminating in the BSE fiasco,¹ and many people are deeply uneasy about the huge opportunities presented by areas of science including biotechnology and information technology, which seem to be advancing far ahead of their awareness and assent. In turn, public unease, mistrust and occasional outright hostility are breeding a climate of deep anxiety among scientists themselves. (Select Committee, 2000, p. 11)

More than 45 years ago, Schwab (1962) advocated a shift of emphasis for school science away from the learning of scientific knowledge (the products of science) towards an understanding of the processes of scientific inquiry on the grounds that it can ensure “a public which is aware of the conditions and character of scientific enquiry, which understands the anxieties and disappointments that attend it, and which is, therefore, prepared to give science the continuing support which it requires” (p. 38). More significantly, a focus on history, philosophy and sociology of science (HPS) in the school science curriculum can play a key role in bringing about a more critical understanding of scientists and scientific practice. A related argument advanced by Shamos (1993) is that enhanced scientific literacy is a defence against what he sees as the anti-science and neo-Luddite movements that are (in his words) “threatening to undermine science”. The school science curriculum, he argues, “should be the forum for debunking the attempts of such fringe elements to distort the public mind, first by exposing their tactics, and then by stressing over and over again the central role in science of objective, reproducible evidence” (p. 71).

Arguments that scientific and technological literacy brings benefits to individuals come in a variety of forms. It is commonly argued, for example, that scientifically and technologically literate individuals have access to a wide range of employment opportunities and are well-positioned to respond positively and competently to the introduction of new technologies in the workplace. In recent years, this has been especially true in industries that make extensive use of infor-
CHAPTER 1

Information and communications technology. In addition, it is argued that those who are scientifically literate are better able to cope with the demands of everyday life in an increasingly technology-dominated society, although even casual observation of technological innovation shows that advances are generally in the direction of increased user-friendliness, so that less expertise is needed to cope with a new technology than was needed for the old. Competency is built into the technology! Atkin and Helms (1992) express this view particularly well.

Ordinary, intelligent human beings can get along perfectly well without a knowledge of Newton’s Laws, an understanding of the atomic nature of matter, or even how everyday consumer devices (like TV sets or automobiles) operate. They do it all the time. That is not to say that people are not benefited by such information, of course. But to claim a major place for science education in the schools on the basis of its essentiality in personal and social functioning – as by likening its centrality to reading or calculating – is an exaggeration that misleads the teacher, the student, and the public. (p. 4)

A stronger case is that scientifically literate individuals are better positioned to evaluate and respond appropriately to the supposed “scientific evidence” used by advertising agencies and politicians, and better equipped to make important decisions that affect their health, security and economic well-being. The point at issue here is that particular scientific knowledge, skills and attitudes are essential for everyday life in a complex, rapidly changing and science/technology-dominated society. What that knowledge comprises will be discussed later in the chapter.

Some have argued for the intellectual, aesthetic and moral-ethical benefits conferred on individuals by scientific literacy. For example, C.P. Snow (1962) referred to science as “the most beautiful and wonderful collective work of the mind of man”, thus making it as crucial to contemporary culture as literature, music and fine art. Richard Dawkins (1998) expresses similar views: “the feeling of awe and wonder that science can give us is one of the highest experiences of which the human psyche is capable. It is a deep aesthetic passion to rank with the finest that music and poetry can deliver” (p. x). Schibeci and Lee (2003) argue for the deep personal benefits of studying and engaging in science, which they characterize as an “intellectually enabling and ennobling enterprise” (p. 188). Others have claimed that appreciation of the ethical standards and code of responsible behaviour within the scientific community will lead to more ethical behaviour in the wider community – that is, the pursuit of scientific truth regardless of personal interests, ambitions and prejudice (part of the traditional image of the objective and dispassionate scientist) makes science a powerful carrier of moral values and ethical principles: “Science is in many respects the systematic application of some highly regarded human values – integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination” (AAAS, 1989, p. 201). In other words, scientific literacy does not just result in more skilled and more knowledgeable people, it results in wiser people – that is, people well-equipped to make morally and ethically superior decisions.

4
Arguments that increased scientific literacy brings benefits to society as a whole include the familiar and increasingly pervasive economic argument and the claim that it would enhance democracy and promote more responsible citizenship. The first argument sees scientific literacy as a form of human capital that sustains the economic well-being of a country. Put simply, continued economic development brought about by enhanced competitiveness in international markets depends on science-based research and development, technological innovation and a steady supply of well-trained scientists, engineers and technicians. The Government of Canada has long promoted this view:

Our future prosperity will depend on our ability to respond creatively to the opportunities and challenges posed by rapid change in fields such as information technologies, new materials, biotechnologies and telecommunications … To meet the challenges of a technologically driven economy, we must not only upgrade the skills of our work force, we must also foster a lifelong learning culture to encourage the continuous learning needed in an environment of constant change. (Government of Canada, 1991, pp. 12 & 14)

As I will argue in Chapter 8 with respect to the distinctive language of science, the discourse of any group is suffused with assumptions, beliefs, attitudes and values. Thus, teaching newcomers to use the discourse of the social group is a crucial element in the business of enculturating them into a community of practice, helping to create a particular view of the world and to foster particular attitudes and habits. Skilful and continued deployment of a particular discourse creates a particular social reality. Indeed, rhetoric becomes reality and those who think differently and have different values are regarded as deviant or aberrant. Thus, Lankshear et al. (1996) argue that the pressures exerted by business and industry on schools to provide more “job ready” people can be seen as part of an overt sociotechnical engineering practice in which new capitalism is creating “new kinds of people by changing not just their overt viewpoints but their actual practices” (p. 22). In short, the business community is re-engineering people in its own image! The impact on Ontario schools has been considerable. It is now rare to find teachers who are prepared to question Ministry of Education directives, much less to design and implement curriculum experiences that challenge these new societal assumptions or address controversial issues. Instead, most teachers comply with all policy guidelines, ensure coverage of the prescribed curriculum content as efficiently as possible, avoid anything controversial, implement standardized assessment schemes to measure designated learning outcomes, and fill in the myriad boxes in the ever-expanding catalogue of official report cards (Alsop, 2009).

At the opposite end of the political spectrum is the argument that increased scientific literacy will promote more democratic decision-making (by encouraging everyone to exercise their democratic rights) and more effective decision-making (by encouraging people to exercise their democratic rights more wisely and responsibly).² In the words of Chen and Novick (1984), enhanced scientific literacy is a means “to avert the situation where social values, individual involvement,
responsibility, community participation and the very heart of democratic decision making will be dominated and practiced by a small elite” (p. 425). Democracy is strengthened when all citizens are equipped to confront and evaluate socio-scientific issues (SSI) knowledgeably and rationally, rather than (or as well as) emotionally,\(^3\) and to make informed decisions on matters of personal and public concern. As Dawkins (1998) remarks: “lawyers would make better lawyers, judges better judges, parliamentarians better parliamentarians and citizens better citizens if they knew more science and, more to the point, if they reasoned more like scientists” (p. 113). It is also the case, as Sagan (1995) notes, that some scientists would be better scientists and some engineers would be better engineers if they were more cognizant of the social, cultural, ethical, environmental and economic consequences of what they do. In Hodson (2008) I promoted the view that scientific literacy is the driving force for sociopolitical action – an argument that will be explored at length in a later book. Roth and Barton (2004) make essentially the same point: “critical scientific literacy is inextricably linked with social and political literacy in the service of social responsibility” (p. 10). In common with Roth and Lee (2002, 2004), they recognize that significant impact on SSI decision-making is more likely through collective action than individual efforts, thus shifting the ultimate focus of education for scientific literacy towards effective public practice, summed up by the increasingly popular notion of enhanced public engagement with science.

One further argument for seeking enhanced scientific literacy is that it might also be the most effective way to address: (i) the naïve trust that many people have in whatever information they obtain from a few minutes searching the Internet, (ii) the suspicion with which many people regard any argument that deploys statistics, on the grounds that “statistics can prove anything”, (iii) the increasing acceptance of New Age beliefs, such as iridology, reflexology and the healing properties of crystals, and (iv) the continuing fascination that many people have with astrology and the paranormal.

### DEFINING SCIENTIFIC LITERACY

Given all this rhetoric and debate about scientific literacy, and the large number of official and semi-official documents promoting it (AAAS, 1993, UNESCO, 1993; National Research Council, 1996; Council of Ministers of Education, 1997; Millar & Osborne, 1998; Organization for Economic Cooperation and Development, 1999; Goodrum et al., 2000; Department of Education (RSA), 2002), one might expect: (i) clear consensus regarding its definition and (ii) the availability of unambiguous guidelines concerning a curriculum capable of achieving it. Such is not the case, as reviews by Gräber and Bolte (1997), Laugksch (2000), De Boer (2001) and Roberts (2007) make abundantly clear.\(^4\)

It would be a very odd state of affairs for someone to claim scientific literacy and to admit ignorance of the major theoretical frameworks of biology, chemistry, physics and the earth sciences. Scientific literacy clearly has a content component,
SCIENTIFIC LITERACY AND THE KEY ROLE OF HPS

though the precise nature of that content is a matter of debate – a debate that is outside the scope of this book. What is of concern in this book are those elements of the history of science, philosophy of science and sociology of science that constitute a satisfactory understanding of the nature of science (NOS), long regarded as a major component of scientific literacy and an important learning objective of science curricula.5 Indeed, the promotion of NOS in official curriculum documents has become so prominent that Dagher and BouJaoude (2005) have stated: “improving students’ and teachers’ understanding of the nature of science has shifted from a desirable goal, to being a central one for achieving scientific literacy” (p. 378, emphasis added). In making the case for NOS knowledge in the curriculum, Driver et al. (1996) contend that in addition to its intrinsic value, NOS understanding enhances learning of science content, generates interest in science and develops students’ ability to make informed decisions on socioscientific issues based on careful consideration of evidence. There is also an argument, advanced by Erduran et al. (2007) that NOS knowledge (and the wider notion of HPS understanding) is of immense value to teachers, making them more reflective and more resourceful.

In many ways, the long-standing confusion over terms such as “literacy”, “illiteracy” and “literate”, where some writers see literacy as mere functional competence while others see it as a sensitive awareness of the complexities of language, is mirrored in the use of the term “scientific literacy”. Some see “being scientifically literate” as the capacity to read, with reasonable understanding, lay articles about scientific and technological matters published in newspapers and magazines, or posted on the Internet. For example, Miller (2000, 2004) defines it in terms of reading and making sense of the Tuesday science section of The New York Times. Others regard scientific literacy as possession of the knowledge, skills and attitudes deemed necessary for a career as a professional scientist or engineer. We need to ask whether scientific literacy is more akin to what a “literate” or well-educated person would know and be able to do, or more akin to a basic or functional literacy – that is, being able to read at an acceptable level of comprehension?6 Some years ago, Atkin and Helms (1992) asked two key questions about scientific literacy. First, does a person need to know science in the same sense that they need to know their mother tongue? Second, is the ability to use scientific knowledge in the way one uses language essential for adequate functioning and responsible citizenship? To both questions, their answer was “No”. An alternative question is: “Does one need to be literate in order to achieve scientific literacy?” Now the answer is clearly “Yes”, regardless of whether the argument for scientific literacy focuses on the preparation of future scientists or the education of responsible citizens.7 Engagement in science is not possible without a reasonable level of literacy. As Anderson (1999) states: “reading and writing are the mechanisms through which scientists accomplish [their] task. Scientists create, share, and negotiate the meanings of inscriptions – notes, reports, tables, graphs, drawings, diagrams” (p. 973). Scientific knowledge cannot be articulated and communicated except through text, and its associated symbols, diagrams, graphs and equations. Moreover, the specialized language of science makes it possible
for scientists to construct an alternative interpretation and explanation of events and phenomena to that provided by ordinary, everyday language. Indeed, it could be said that learning the language of science is synonymous with (or certainly coincident with) learning science, and that doing science in any meaningful sense requires a reasonable facility with the language.\(^8\) It is scientific language that shapes our ideas, provides the means for constructing scientific understanding and explanations, enables us to communicate the purposes, procedures, findings, conclusions and implications of our inquiries, and allows us to relate our work to existing knowledge and understanding.  

Without text, the social practices that make science possible could not be engaged: (a) the recording and presentation and re-presentation of data; (b) the encoding and preservation of accepted science for other scientists; (c) the peer reviewing of ideas by scientists anywhere in the world; (d) the critical re-examination of ideas once published; (e) the future connecting of ideas that were developed previously; (f) the communication of scientific ideas between those who have never met, even between those who did not live contemporaneously; (g) the encoding of variant positions; and (h) the focusing of concerted attention on a fixed set of ideas for the purpose of interpretation, prediction, explanation, or test. The practices centrally involve texts, through their creation in writing and their interpretation, analysis, and critique through reading. (Norris & Phillips, 2008, p. 256)  

Kintgen (1988 – cited by Osborne, 2002, p. 213) identifies four stages of literacy: first, the *signature* stage, that is, the ability to read and write one’s own name; second, the *recitation* stage, where an individual is able to read all (or most) of the words in a passage but has little understanding of the overall meaning or its significance and implications; third, the *comprehension* stage, that is, the ability to make sense of unfamiliar material at the literal level; fourth, the *analytical* stage, comprising the ability to analyze, interpret, critique and evaluate text, including media reports. It is this fourth level of literacy that we should be seeking, a stage of development that necessitates substantial conceptual understanding as well as linguistic capability. Proficient and critical reading of science text, whether first order or second order literature, involves more than just recognizing all the words and being able to locate specific information; it also involves the ability to (i) determine when something is an inference, a hypothesis, a conclusion or an assumption, (ii) distinguish between an explanation and the evidence for it, and (iii) recognize when the author is asserting a claim to “scientific truth”, expressing doubt or engaging in speculation. Without this level of interpretation the reader will fail to grasp the essential scientific meaning. Put simply, learning to think and reason scientifically requires a measure of familiarity and facility with the forms and conventions of the language of science (Norris & Phillips, 2003). It is not solely a matter of recognizing the words, it is also an ability to comprehend, evaluate and construct arguments that link evidence to ideas and theories, and use that understanding in new situations. Thus, teaching about the language of science, and its use in scientific argumentation, should be a key element in
SCIENTIFIC LITERACY AND THE KEY ROLE OF HPS

Science education at all levels. It is the strength and plausibility of the argument and its supporting evidence that scientists consider when judging any claim to knowledge. All aspects of the “case” need to be appraised: Was the method well-chosen and well-executed? How trustworthy is the data? Does the conclusion follow from the data and its interpretation? Are there alternative interpretations and conclusions? Does the argument take account of existing knowledge, and does it build on it or refute it? Does the conclusion constitute new knowledge? How plausible is the overall case? And so on. The construction and appraisal of argument is a crucial dimension of scientific practice. Consequently, understanding the nature of scientific arguments and being able to construct and evaluate them is a crucial element of scientific literacy. Thus, we need to provide frequent and rich opportunities for students to explore and use the language of science: to read and write science, discuss the meaning of scientific text, note how ideas are supported by evidence, construct plausible arguments and evaluate arguments constructed by others. Because most people obtain the bulk of their knowledge of contemporary science and technology from television, newspapers, magazines and the Internet, the capacity for active critical engagement with scientific text is a crucial element of scientific literacy. Indeed, it could be claimed that it is the most important element.

To be fully scientifically literate, students need to be able to distinguish among good science, bad science and non-science, make critical judgements about what to believe, and use scientific information and knowledge to inform decision making at the personal, employment and community level. In other words, they need to be critical consumers of science. This entails recognizing that scientific text is a cultural artifact, and so may carry implicit messages relating to interests, values, power, class, gender, ethnicity and sexual orientation. (Hodson, 2008, p. 3)

LITERACY OR LITERACIES?

What else can be regarded as essential components of scientific literacy? Understanding the complex relationships among science, technology, society and environment? Knowing about the historical development of the “big ideas” of science and the sociocultural and economic circumstances that led to the development of key technologies? Knowing something about the complex organizational structure of scientific practice and its systems of control and ownership? Being aware of contemporary applications of science? Having the ability to use science in everyday problem solving? Holding a personal view on controversial issues that have a science and/or technology dimension? Possessing a basic understanding of global environmental issues?

We can begin to answer these questions by taking note of common practice in linguistics, and especially the teaching of English as a second language. The notion of a “general understanding” of English has been replaced by an array of functional understandings that are situation specific. Courses are routinely
devised along the lines of English for foreign-trained nurses practising in the United Kingdom or English for Russian engineers working in the United States, on the grounds that literacy needs are highly context dependent. The same principle applies to scientific knowledge and its associated scientific literacy. For example, while biochemists are interested in the chemical reactions constituting digestion, nutritionists are more concerned with “calorie counts”, and while an evolutionary biologist might choose to classify an animal as mammal, reptile or fish, an ecologist would prefer to employ categories such as lives on land and lives in water, or carnivore, insectivore and herbivore. How we choose to classify depends on (i) what we know (our conceptual understanding) and (ii) our purpose in classifying. Is the classification intended to inform the study of evolutionary processes? Is it part of preparation for ecological work? Or is it to help us find our way around the local zoo? Similarly, because their primary concerns are different, physicists and engineers confront the world with very different theoretical frameworks – for example, a commitment to the principle of conservation of energy versus daily concern about heat loss (and the means to minimize it) and deployment of a theoretical position that seems to envisage heat as a fluid that flows. Indeed, because the problems they face may be unique and ill-defined, engineers and other technologists often have to create purpose-made theoretical models by drawing on content from several scientific disciplines. It follows that there is value in thinking about different scientific literacies for different purposes and for different sociocultural contexts.

Shen (1975) identifies three such categories: practical scientific literacy, civic scientific literacy and cultural scientific literacy. Practical scientific literacy is knowledge that can be used by individuals to cope with life’s everyday problems relating to diet, health, consumer preferences, technological competence, and so on; civic scientific literacy comprises the knowledge, skills, attitudes and values necessary to play a full and active part in key decision-making in areas such as use of natural resources, energy policy, moral-ethical issues relating to medical and technological innovations, and environmental protection; cultural scientific literacy involves knowing something of the ideas and theories of science that constitute major cultural achievements and the sociocultural and intellectual environment in which they were produced. The term cultural scientific literacy is used to signal belief that answers to deeply-rooted questions such as the nature and origin of life, and of the cosmos, collectively constitute a cultural heritage and resource to which everyone should have access. Layton et al. (1993) have described this aspect of scientific literacy as “recognition and appreciation of “the cathedrals of science”, science as a majestic achievement of the human intellect and spirit” (p. 15)

In the context of this book the notion of environmental literacy is particularly helpful. Although the term itself is not universally accepted, with some writers opting for “ecological literacy”, “education for sustainability” or even “ecological citizenship” (Hart, 2007), there is some general agreement on its three major components: (i) knowledge and understanding of the environment and the impact of people on it (including content knowledge such as the hydrological cycle,
food webs, mechanisms of climate change and ozone depletion); (ii) attitudes and values that reflect feelings of concern for the environment and foster a sensitive environmental ethic; (iii) a sense of responsibility to address issues and resolve environmental problems through participation and action, both as individuals and collectively. The importance of environmental or ecological literacy to life in the 21st century is graphically captured by David Orr’s (1992) comments on the consequences of not giving it prominence in the curriculum.

A generation of ecological yahoos without a clue why the color of the water in their rivers is related to their food supply, or why storms are becoming more severe as the planet warms. The same persons as adults will create businesses, vote, have families, and above all, consume. If they come to reflect on the discrepancy between the splendor of their private lives in a hotter, more toxic and violent world, as ecological illiterates they will have roughly the same success as one trying to balance a checkbook without knowing arithmetic. (p. 86)

Miller and Kimmel (2001) have defined biomedical literacy as the specialized knowledge needed by an individual facing a personal decision on gene therapy or seeking to understand and participate in debate on research involving embryonic stem cells. Although it is possible to identify other specific scientific literacies – for example, industrial scientific literacy, for management personnel and plant workers in specific manufacturing environments, professional scientific literacy, to serve the needs of those whose future work lies in science and science-related professions, recreational scientific literacy, focusing on the science underpinning gardening, scuba-diving, car maintenance, and so on – there is little to be gained by doing so here, save to argue for the adoption of the term critical scientific literacy, where “critical” is taken to mean rigorous, analytical, logical, thorough, open-minded, skeptical, careful and reflective. I use the term critical scientific literacy on the grounds that the most important function of scientific literacy is to confer a measure of intellectual independence and personal autonomy: first, an independence from authority; second, a disposition to test the plausibility and applicability of principles and ideas for oneself, whether by experience or by a critical evaluation of the testimony of others; third, an ability to form intentions and choose a course of action in accordance with a scale of values that is self-formulated. In other words, the fundamental purpose of scientific literacy (and technological literacy) is to help people think for themselves and reach their own conclusions about a range of issues that have a scientific and/or technological dimension. As Désautels et al. (2002) put it: “Instead of a liberal education, we seek a liberating education” (p. 266).

The science underpinning socioscientific issues is sometimes complex and uncertain. It is frequently outside the knowledge store of most citizens. Even among scientists, only those working at the research frontier are likely to have a full understanding of all the key elements. As Lewontin (2002) points out, this poses a problem for a democratic society.

On the one hand, the behavior of the state is supposed to reflect the popular will, as determined either by a direct appeal to the opinion of the people or
through the intermediary of their elected representatives. On the other hand, the esoteric knowledge and understanding required to make rational decisions in which science and technology are critical factors lie in the possession of a small expert elite. Even within the ranks of “scientists” only a tiny subset have the necessary expertise to make an informed decision about a particular issue.

Although we are increasingly dependent on experts, it is undesirable to cede all deliberation and all policy decisions to a particular small group of experts. Every citizen needs sufficient understanding about the relevant science (if not understanding of the science) to play a part. Every citizen needs to develop what Lorraine Code (1987) calls “a policy of circumspection” and what McPeck (1981) calls “reflective skepticism” – that is, the disposition to question and to seek the opinions of others on all the science that underpins the issues they confront in everyday life. Code (1987) notes that “one of the most important and difficult steps in learning who can be trusted is realizing that authority cannot create truth” (p. 248). Balance is the key: not blind acceptance of the views espoused by those who are seen, or see themselves, as experts; not cynicism and distrust of all experts. Guy Claxton (1997) captures the essence of this position particularly well: “[students] need to be able to see through the claims of Science to truth, universality, and trustworthiness, while at the same time not jumping out of the frying-pan of awe and gullibility, in the face of Science’s smugness and superiority, into the fire of an equally dangerous and simplistic cynicism, or into the arms of the pseudo-certainties of the New Age” (p. 84). Balance is encapsulated in the notion of intellectual independence. As Munby (1980) notes: “One can be said to be intellectually independent when one has all the resources necessary for judging the truth of a knowledge claim independently of other people” (p. 15).

As I will argue in a subsequent book, a measure of politicization of students can be achieved by assisting them to recognize that: (i) the benefits of technological innovations can sometimes be accompanied by unwelcome and unexpected side effects, including social dislocation and adverse environmental impact; (ii) the benefits and hazards are not always distributed equably within and between societies, creating major sociopolitical concerns; and (iii) new scientific developments and new technologies frequently create complex moral and ethical dilemmas that challenge currently accepted values and beliefs. Confronting these realities, formulating their own position and planning appropriate action will require students to invest their scientific and technological literacy with a sharp critical edge. Part of that critical edge entails understanding both the power and limitation of scientific discourse and argumentation, and “being able to discriminate between Science and Scientism – the illicit attempt to give warrant and status to one’s claims by presenting them as if they were Scientifically proven or justified; and developing the disposition to do so in the course of daily life” (Claxton, 1997, p. 83 – capitals in original).
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SCIENCE AND TECHNOLOGY

As evident in the foregoing, any discussion of scientific literacy raises questions about technology, the relationship between science and technology, and the meaning of technological literacy. While science can be regarded as a search for explanations of phenomena and events in the natural world, technology is the means by which humans modify nature to meet their needs and wants, and better serve their interests. While it is easy to think of technology in terms of artifacts (computers, aeroplanes, microwave ovens, pesticides and fertilizers, birth control pills, water treatment plants, power stations, and the like), it is important to remember that it also includes the knowledge, skills and infrastructure necessary for the design, manufacture, operation and maintenance of those artifacts. Although there can be some important differences between them in terms of purposes, concepts, procedures and criteria for judging acceptability of solutions, science and technology are closely related. Clearly, scientific understanding of the natural world is the basis for much of contemporary technological development. The design of computer chips, for instance, depends on detailed understanding of the electrical properties of silicon and other materials, and the design of a drug to fight a particular disease is made possible by knowledge of how the structures of proteins and other biological molecules determine their interactions. Conversely, technology is essential to much contemporary scientific research. Current rates of progress would be impossible without microscopes, telescopes, infra red spectrometers, particle accelerators and DNA sequencers, while running simulations to explore the complexities of the models that meteorologists build to study global climate change is just one example of how contemporary science requires elaborate computer technology. In fields such as high energy physics and nanotechnology it is very difficult, if not impossible, to disentangle science and technology. Indeed, it often makes more sense to speak of technoscience. Johnson (1989) sums up the relationship between science and technology as follows:

Technology is the application of knowledge, tools, and skills to solve practical problems and extend human capabilities. Technology is best described as process, but it is commonly known by its products and their effects on society. It is enhanced by the discoveries of science and shaped by the designs of engineering. It is conceived by inventors and planners, raised to fruition by the work of entrepreneurs, and implemented and used by society . . . Technology’s role is doing, making and implementing things. The principles of science, whether discovered or not, underlie technology. The results and actions of technology are subject to the laws of nature, even though technology has often preceded or even spawned the discovery of the science on which it is based. (p. 1 – cited by Lewis & Gagel, 1992, p. 127)

Arnold Pacey’s classic work, The Culture of Technology (published in 1983), defines technological products and practices in terms of a technical aspect (knowledge, skills, techniques, tools, machines, resources, materials and people), an organizational aspect (including economic and industrial activity, professional
activity, users, consumers and trade unions) and a cultural aspect (goals, values, beliefs, aspirations, ethical codes, creative endeavour, etc.). In similar vein, Carl Mitcham (1994) conceptualizes technology in terms of four aspects: (i) as objects, artifacts and products; (ii) as a distinctive form of knowledge, separate from science; (iii) as a cluster of processes (designing, constructing or manufacturing, evaluating, systematizing, etc.); and (iv) as volition (the notion that technology is part of our human will and, therefore, an intrinsic part of our culture). Both writers note that technology reflects our needs, interests, values and aspirations, thus providing a valuable counter to the somewhat bleak views of technological determinism portrayed in many science fiction stories and movies – the idea that current technology determines future technology and that human beings must adapt to its dictates (see Winner, 1977, for an extended discussion). Remarks such as “You can’t stop progress”, “It’s inevitable” and “That’s what we will have to get used to” are commonplace and reveal a strong sense of individual and collective disempowerment and a feeling that technological development and change are in the hands of others, if not of technology itself. An essential step in pursuit of critical scientific and technological literacy is the application of a social and political critique capable of challenging the notion of technological determinism. We control technology and its social and environmental impact, if we have the will and the political literacy to do so. More significantly, we can control the controllers and redirect technology in such a way that adverse environmental impact is reduced (if not entirely eliminated) and issues of freedom, equality and justice are kept in the forefront of discussion in the establishment of policy. These matters are outside the scope of this book but will be dealt with at length in a book currently in preparation.

In arguing the case for the cultivation of technological thinking to be an integral part of every student’s education, the Association for Science Education (1988) identified four inter-related strands: technological literacy – familiarity with the content and methods of a range of technologies; technological awareness – recognition of the personal, moral, social, ethical, economic and environmental implications of technological developments; technological capability – the ability to tackle a technological problem, both independently and in cooperation with others; information technology – competence and confidence in the technological handling of information. In a similar attempt to delineate the field of technology education, Layton (1993) employs a complex classification system based on six “functional competencies”:

- Technological awareness or receiver competence: the ability to recognize technology in use and acknowledge its possibilities.
- Technological application or user competence: the ability to use technology for specific purposes.
- Technological capability or maker competence: the ability to design and make artifacts.
- Technological impact assessment or monitoring competence: the ability to assess the personal and social implications of a technological development.
— Technological consciousness or paradigmatic competence: an acceptance of, and an ability to work within, a “mental set” that defines what constitutes a problem, circumscribes what counts as a solution and prescribes the criteria in terms of which all technological activity is to be evaluated.

— Technological evaluation or critic competence: the ability to judge the worth of a technological development in the light of personal values and to step outside the “mental set” to evaluate what it is doing to us.

A similar approach has been adopted by Gräber et al. (2002), culminating in a 7-component competency-based model of scientific literacy comprising subject competence, epistemological competence, learning competence (using different learning strategies to build personal scientific knowledge), social competence (ability to work in a team on matters relating to science and technology), procedural competence, communicative competence and ethical competence. My own inclination is simply to extend the three major elements of science education listed in endnote 8 to include technology, together with the dimensions of politicization and preparation for sociopolitical action.

— Learning science and technology – acquiring and developing conceptual and theoretical knowledge in science and technology, and gaining familiarity with a range of technologies.

— Learning about science and technology – developing an understanding of the nature, methods and language of science and technology; appreciation of the history and development of science and technology; awareness of the complex interactions among science, technology, society and environment; and sensitivity to the personal, social, economic, environmental and moral-ethical implications of particular technologies.

— Doing science and technology – engaging in and developing expertise in scientific inquiry and problem-solving; developing confidence and competence in tackling a wide range of “real world” technological tasks and problems.

— Engaging in sociopolitical action – acquiring (through guided participation) the capacity and commitment to take appropriate, responsible and effective action on science/technology-related matters of social, economic, environmental and moral-ethical concern, and the willingness to undertake roles and responsibilities in shaping public policy related to scientific and technological developments at local, regional, national and/or global levels.

Sometimes there is value in teachers emphasizing the differences between science and technology, sometimes it is more important and more interesting to direct attention to the similarities. Sometimes it is important for students to think in a purely scientific way, sometimes it is crucial that they learn to think in a technological way (e.g., like an architect, doctor or engineer) – a frame of mind predicated on a willingness to draw on knowledge from a range of disciplines in order to address complex real world issues and problems. Some issues of demarcation between science and technology are considered in Chapter 5.

Any discussion of technological literacy inevitably raises important issues relating to computer technology. The World Wide Web, computer-aided design,
word processing, data processing and electronic transfer of information have
become the engines of economic growth and have fundamentally changed the
ways we learn, communicate and do business. Computer literacy extends well
beyond the acquisition of basic computer skills, to encompass: (i) consideration
of the socioeconomic impact of computer technology and the globalization it has
accelerated; (ii) the legal issues and moral-ethical dilemmas associated with open
access to information, censorship and data protection; (iii) the capacity to evaluate
information for accuracy, relevance and appropriateness; and (iv) the ability to
detect implied meaning, bias and vested interest. In these latter dimensions there
is significant overlap with media literacy – an area of concern that is well outside
the scope of this book. It should also be noted that scientific and technological
literacy necessarily includes some basic understanding of mathematics, such as
familiarity with simple algebraic equations and the capacity to interpret graphical
and statistical data. Duschl et al. (2007) note that encouraging students to express
their ideas in mathematical form (especially graphical representation) helps them
to clarify and develop their scientific understanding, and can sometimes lead to
them “noticing new patterns or relationships that otherwise would not be grasped”
(p. 153). The notion of scientific and technological literacy I wish to develop also
includes some historical understanding of the dependence of science on mathe-
matics. For example, Kepler could not have derived his laws of planetary motion
without knowledge of conic sections accumulated by Greek mathematicians some
1800 years earlier, Hilbert’s theory of integral equations was essential for the
development of quantum mechanics, and Riemann’s differential geometry was
integral to Einstein’s theory of relativity. It is also reasonable to conclude that the
extraordinary growth in scientific knowledge since the 17th century is attributable,
in large part, to developments in mathematics - and, in particular, to the invention
of differential and integral calculus.

TOWARDS A CURRICULUM

The foregoing discussion leads me to conclude that critical scientific and
technological literacy comprises a number of basic components.

− A general understanding of some of the fundamental concepts, ideas, prin-
ciples and theories of science, and the ability to use them appropriately and
effectively.
− Some knowledge of the ways in which scientific knowledge is generated,
validated and disseminated.
− Familiarity with the form, structure and rhetorical purposes of scientific
language.
− The capacity to read and interpret scientific data and, at a general level, to
evaluate their validity and reliability.
− The ability to evaluate a scientific argument or claim to knowledge, and to
present one’s own ideas clearly, concisely and appropriately.
General interest in science, together with a willingness and capacity to update and acquire new scientific knowledge.

Understanding of basic technological concepts, principles of design and criteria of evaluation.

Possession of a range of basic hands-on technical/technological skills, the capacity and confidence to tackle technological problems, and the willingness to develop new knowledge and skills.

Some awareness of the sociocultural and cognitive circumstances surrounding the history and development of some of the “big ideas” of science, the origin and development of important technologies, and the development of mathematics.

An appreciation of the complexity of inter-relationships among science, technology, society and environment.

A commitment to critical understanding of contemporary socioscientific issues at the local, regional, national and global levels, including their historical roots and underlying values, together with a willingness to take appropriate and responsible action, and encourage others to do so.

The capacity and willingness to address moral-ethical issues associated with scientific research and the deployment of scientific knowledge and technological innovations.

It is immediately apparent that issues in the history, philosophy and sociology of science impact on all these components, either directly or indirectly. This is true even of the first item, if one takes the view that understanding and using an item of scientific knowledge entails knowledge of its role and status as well as its strengths, weaknesses and relationships to other knowledge items. In other words, as argued in Hodson (2008), scientific literacy thus constructed is located just as much in learning about science and in doing science as it is in learning science.

No science curriculum can equip citizens with thorough first-hand knowledge of all the science underlying every important issue. Moreover, much of the scientific knowledge learned in school, especially in the rapidly expanding fields of the biological sciences, will be out-of-date within a few years of leaving school and so of little value in addressing socioscientific issues. However, science education can enable students to understand the significance of knowledge presented by others, and it can enable them to evaluate the validity and reliability of that knowledge and to understand why scientists often disagree among themselves on such major matters as climate change (and its causes) without taking it as evidence of bias or incompetence. What is too often unrecognized by science teachers, science textbooks and curricula, and by the wider public, is that dispute is one of the key driving forces of science. Hence controversial issues – no matter whether the controversy focuses on conceptual issues, procedural issues or moral-ethical issues – should be an essential component of a curriculum aimed at critical scientific literacy. Indeed, I would argue that teachers have a duty to assist students in facing and resolving such matters.
Education should not attempt to shelter children from even the harsher controversies of adult life, but should prepare them to deal with such controversies knowledgeably, sensibly, tolerantly and morally. (Qualifications & Curriculum Authority, 1998, p. 56)

Of course, students also need to know that scientists can and do make mistakes, and that bias and incompetence do sometimes occur. In other words, they need to have a clear understanding of what counts as good science (i.e., a well-designed inquiry and a well-argued conclusion) and be able to identify the nature of any inadequacies, errors and biases. In common with the case for intellectual independence made earlier in the chapter, Fourez (1997) argues that a key element of scientific literacy is knowing when scientists and other “experts” can be trusted and when their motives and/or methods should be called into question. His point is that while there is often a need to access and utilize expert opinion we do not need to do so uncritically. We can evaluate the quality of data and argument for ourselves, we can look at the extent of agreement among experts and the focus of any disagreements, and we can look at the “track record” of all those who profess expertise. In similar vein, Norris (1995) makes the point that “nonscientists’ belief or disbelief in scientific propositions is not based on direct evidence for or against those propositions but, rather, on reasons for believing or disbelieving the scientists who assert them” (p. 206). Fourez (1997) also argues that scientifically literate individuals know when to leave “black boxes” closed (i.e., making use of a concept, idea or tool in an instrumental way, without necessarily striving to understand it) and when it is important to open it (i.e., to strive for detailed understanding). Consequently, he says, the science curriculum should teach “the right way to use black boxes” (p. 913) as well as the right way to use standard, well-established scientific knowledge, theories, models, metaphors and inter- or multi-disciplinary models of various kinds.

What I am advocating for inclusion in the school science curriculum, as I argue at length in Hodson (2008), are those elements of the history, philosophy and sociology of science that will enable all students to leave school with robust knowledge about the nature of scientific inquiry and theory building, an understanding of the role and status of scientific knowledge, an ability to understand and use the language of science appropriately and effectively, the capacity to analyze, synthesize and evaluate knowledge claims, some insight into the sociocultural, economic and political factors that impact the priorities and conduct of science, a developing capacity to deal with the moral-ethical issues that attend some scientific and technological developments, and some experience of conducting authentic scientific investigations for themselves and by themselves. While we cannot provide all the science knowledge that our students will need in the future (indeed, we do not know precisely what knowledge they will need), and while much of the science they will need to know has yet to be discovered, we do know what knowledge, skills and attitudes will be essential to appraising scientific reports, evaluating scientific arguments and forming a personal opinion about the science and technology dimensions of real world issues. This realiza-
tion constitutes a powerful argument for a major shift of emphasis from learning science to learning about science. An emphasis on what we know (the current emphasis) rather than how we know (part of the approach being advocated) too often leaves students only able to justify their beliefs by reference to the authority of the teacher or textbook. As Östman (1998) points out, the constant focus on a “correct explanations” approach encourages and reinforces the “companion meaning” that the products of the scientific enterprise are “something that everyone will agree upon, if they just use their senses to smell, taste, listen to, and look at nature” (p. 57). In other words, science is seen as a simple and straightforward route to the truth about the universe; scientific knowledge is seen as authoritative, and students are steered towards conformity with received “official” views rather than towards intellectual independence. In contrast, as Lemke (1998) notes, science is “a very human activity, full of biases and accidents, driven by egos and budgets, competitive and sometimes venal, locked into the agendas of larger institutions and social movements: a wonderful and terrible human comedy, like every other part of life” (p. 2). Science is much more than its products: what science says about the world is only part of the story. A much bigger and more important part concerns the ways in which scientists generate and validate that knowledge, establish research priorities and use knowledge to address real world problems.

However much we may teach them about electrical circuits, redox reactions, or genetic recombination, or even about controlled experimentation and graphical analysis of quantitative covariation, how much better able does this really make them to decide when they trust expert opinion and when they should be skeptical of it? If we teach more rigorously about acids and bases, but do not tell students anything about the historical origins of these concepts or the economic impact of the technologies based on them, is the scientific literacy we are producing really going to be useful to our students as citizens? (Lemke, 2001, pp. 299 & 300)

If students acquire good learning habits and positive attitudes towards science during the school years it will be relatively easy for them to acquire additional scientific knowledge later on, as and when the need arises, provided that they have also acquired the language skills to access and evaluate relevant information from diverse sources. Of course, to be scientifically literate in the sense I am arguing for in this chapter, students will not only need the language skills to access knowledge from various sources, but also the capacity to participate comfortably in public debate about SSI and express their knowledge, views, opinions and values in a form appropriate to their purpose and the audience being addressed.

The robust familiarity with key issues in the history, philosophy and sociology of science essential to critical scientific literacy requires lengthy and close contact with someone already familiar with them – that is, with a teacher or scientist who can provide appropriate guidance, support, experience and criticism. Formal education is crucial in laying the appropriate foundation. At present, in many schools, students often acquire NOS knowledge by accident, picking up ideas more by what is absent than from any deliberate intention on the part of the teacher.
(Munby & Roberts, 1998). Hodson (2008) identifies and clarifies a number of major items for inclusion in the curriculum from the vast literatures of history of science, philosophy of science and sociology of science. This book is concerned with ways of “translating” these items into a robust and coherent curriculum.

Three points about curriculum construction should be made at this stage. First, the goal of improving NOS understanding is often hampered by stereotyped images of science and scientists consciously or unconsciously built into school science curricula (Hodson, 1998b) and perpetuated by science textbooks (McComas, 1998). As a first priority, therefore, teachers need to present students with a more authentic science education – that is, an approach to learning science that has elements in common with the practices of the scientific community. Gilbert (2004) describes authentic science education in terms of four major characteristics.

First, it would more faithfully represent the processes by which science is conducted and its results are socially accepted; it should be more historically and philosophically valid. Second, it would reflect the core element of creativity that has made science one of the major cultural achievements of humanity in recent centuries. Third, it would provide a minimalist network of ideas with which to provide satisfactory explanations of phenomena in the world-as-experienced. Lastly, it would be capable of underpinning those technological solutions to human problems that are the basis of prosperous economies, social well-being, and the health of individuals (p. 116).

Second, the formulation of a prescribed list of NOS items or a set of “required beliefs” about the nature of science is both educationally undesirable and inappropriate to the goal of critical scientific literacy. The intent of the learning about science component of the curriculum is not inculcation of particular views, and we should no more tolerate this position than we should approve the relativist position in which any view is regarded as equally acceptable to any other. Rather, the intention is to confront students with a range of alternatives, engage them in critical debate, with appropriate stimulus and guidance, and assist them in formulating their own views – views for which they can argue and for which they can provide a robust and coherent “warrant for belief”.

Third, the drive for authenticity should be tempered by considerations of appropriateness. Not everything in the literature of history, philosophy and sociology of science is appropriate for young minds – see Brush (1974), Matthews (1998), Allchin (2004a) and Bell (2004) for a discussion of this proposition, and Davson-Galle (2008) for a vigorous argument against NOS as an element of a compulsory science curriculum. In my view, we should select NOS items for the curriculum in relation to other educational goals – for example, motivating students and assisting them in developing positive attitudes towards science, paying close attention to the cognitive goals and emotional demands of specific learning contexts, creating opportunities for students to experience doing science for themselves, enabling students to address complex socioscientific issues with critical understanding, attending to concerns of multiculturalism and antiracism, and so on.
The degree of sophistication of the NOS items we include should be appropriate to the stage of cognitive and emotional development of the students and should be compatible with other long and short-term educational goals. There are numerous goals for science education, and education in general, that can, will and should impact on decisions about the NOS content of lessons. Our concern is not just good philosophy of science, good sociology of science or good history of science, not just authenticity and preparation for sociopolitical action . . . but the educational needs and interests of the students – all students. Selection of NOS items should consider the changing needs and interests of students at different stages of their science education, as well as taking cognizance of the views of “experts” and promoting the wider goals of (i) authentic representation of science and (ii) politicization of students. (Hodson, 2008, p. 182)

Attention in this book is largely concentrated on curriculum structures and teaching and learning methods capable of ensuring that all students are properly equipped to: (i) confront and solve everyday problems that have a science and/or technology dimension; (ii) comprehend the significance of technological developments, understand the science that underpins them and evaluate their value and appropriateness; and (iii) address socioscientific and technological issues in local, regional, national and global contexts, formulate a personal position on the issues and take appropriate action.

NOTES

1 The report notes that “in the run-up to the BSE crisis in 1996, uncertainties were insufficiently acknowledged, with advisers and ministers representing the lack of any “sound scientific” evidence for a risk as evidence that it could not occur. It was thus common for politicians to deliver unequivocal assurances of safety” (Select Committee, 2000, p. 1).


3 The role of emotions in decision-making on controversial issues will be examined in a subsequent book.

4 Roberts (2007) reviews a number of publications that address the meaning of scientific literacy (SL). He categorizes them in terms of five basic approaches or “conceptual methodologies”: first, the historical approach, tracing the development of notions of SL since the late 1950s; second, approaches that try to identify “types” or “levels” of SL; third, discussion of SL focused on the notion of literacy itself; fourth, discussion of SL in terms of the needs and interests of practising scientists; fifth, an approach that identifies situations or contexts in which SL is presumed to be necessary or valuable.

5 In recent publications, Lederman (2006, 2007) seeks to restrict use of the term nature of science to the characteristics of scientific knowledge (i.e., to epistemological considerations). This is an odd notion, given that much of our scientific knowledge and, therefore, consideration of its status, validity and reliability, is intimately bound up with the design, conduct and reporting of scientific investigations. Moreover, teaching activities focused on NOS often include empirical investigations. Thus, as Ryder (2009) points out, the conduct of scientific inquiry and NOS are related both conceptually and pedagogically. In common with definitions adopted by Osborne et al. (2003), Clough (2006), Clough and Olson (2008), Hodson (2008) and Wong and Hodson (2009), my conception of NOS encompasses the characteristics of scientific inquiry, the role and status of the scientific knowledge it generates, how scientists work as a social group, and how science impacts and is impacted by the social context in which it is located.
CHAPTER 1

Osborne (2002) resists the notion that scientific literacy is a quality that an individual possesses or does not possess. Rather, he says, “scientific literacy exists on a continuum between being totally illiterate (and totally dependent on others) to acknowledged expertise (and minimal intellectual dependence). Knowing and understanding both some of the content and the appropriate use of language of science is an essential component on the path towards such scientific literacy” (p. 214).

I emphatically reject the suggestion by Klopfer (1969) that this distinction should be reflected in a differentiated school science curriculum: “One curricular stream . . . designed for students planning to enter careers as scientists, physicians, and engineers . . . the other . . . designed for students who will become the nonscientist citizenry . . . housewives, service workers, salesmen, etc. . . . Differentiation of students (should) begin at about age fourteen when they choose the high school they will attend” (p. 203). My own view is more closely aligned with Jerry Wellington’s (2001) argument that every student’s science education should comprise components that reflect the three major justifications for particular science content: (i) the intrinsic value of science education; (ii) the citizenship argument; (iii) utilitarian arguments. In an attempt at compromise, the authors of Beyond 2000: Science Education for the Future (Millar & Osborne, 1998) state that science education between the ages of 5 and 16 (the years of compulsory schooling in the UK) should comprise a course to enhance general scientific literacy, with more specialized science education delayed until later years: “the structure of the science curriculum needs to differentiate more explicitly between those elements designed to enhance ‘scientific literacy’, and those designed as the early stages of a specialist training in science, so that the requirement for the latter does not come to distort the former” (p. 10). Donnelly (2005) is vociferous in his condemnation of this proposal and the potentially adverse impact it would have on the science education of the majority of students by greatly reducing the theoretical content of the curriculum.

In a number of publications (Hodson, 1992a, 1994, 1998a) I have argued that science education is best regarded as comprising three major elements: learning science (an emphasis on content), learning about science (concern with HPS issues and science-technology-society-environment (STSE) dimensions); doing science (first hand experience of scientific inquiry). In recent years (Hodson, 2003), I have added a fourth component: engaging in sociopolitical action.

A survey in the United Kingdom showed that most school-age students spend more time accessing science and science-related materials on the Internet than they do in science lessons (Department for Education & Skills, 2002 – cited by Wellington & Britto, 2004, p. 208). In general, the popular media report what we might call “frontier science” or “science-in-the-making” (Latour, 1987) and, necessarily, citizens depend on journalists to keep them informed of advances in science and technology; even professional scientists are unable to keep up with the primary literature in all fields and so must depend on others to keep them abreast of change and development.

Science education for (responsible) citizenship, with its emphasis on confronting complex SSI at local, regional, national and global levels, throws up the same kind of issue. Different notions of good or responsible citizenship are evident in different societal contexts: “The concept of good citizenship in an Islamic theocracy is not the same as in the USA, Australia or other industrialized democracies. Likewise, acting as a good citizen with respect to a global science-related issue may conflict with actions taken in response to more local, regional or national concerns” (Jenkins, 2006, p. 207). Murcia (2009) represents scientific literacy by means of a rope metaphor: interwoven threads of conceptual knowledge, NOS knowledge and understanding of the social, political and economic context in which science is located. Individuals acquire understanding and expertise in each of these threads, but the particular balance between the threads is determined by that person’s interests, dispositions and aspirations.

The authors of Taking Science to School, a recent report from the National Research Council (Duschl et al., 2007), argue along similar though narrower lines when they state that students in school who are proficient in science: “(1) know, use, and interpret scientific explanations of the natural world; (2) generate and evaluate scientific evidence and explanations; (3) understand the nature and development of scientific knowledge; and (4) participate productively in scientific practices and discourse” (p. 36).
CHAPTER 2
RESEARCH ON STUDENTS’ VIEWS OF NOS

In planning how best the goal of critical scientific literacy and its attendant understanding of NOS knowledge can be attained we should take steps to ascertain the position from which we are likely to “begin the journey”. Some 40 years ago, David Ausubel (1968) remarked: “If I had to reduce all of educational psychology to just a single principle, I would say this: Find out what the learner already knows and teach him accordingly” (p. 337). This applies just as much to teaching NOS knowledge as to any other aspect of science education. Just as students already have some prior understanding of many of the entities, phenomena and events in the natural world they encounter in science lessons, so they have prior conceptions of science and scientists. These views, which will inevitably impact the ways in which they respond to classroom events, particularly those relating to the collection and interpretation of data, may be different from the views that form the intended learning about science components of the curriculum, and will certainly be different from the ideas about science implied by the basic components of critical scientific literacy articulated in Chapter 1.

Students will, of course, use their existing NOS views as a lens through which to make sense of events in the classroom, with considerable potential for misunderstanding if the teacher plans her/his lessons in accordance with one view of science and students interpret the activity in accordance with a different one. Over the past 25 years or so, extensive research into students’ alternative frameworks of understanding in science has alerted teachers to the potential learning difficulties likely to arise from a mismatch between a student’s conceptual framework and that assumed by the teacher in designing curriculum experiences. Significant mismatch between a student’s understanding of the role, status and origin of scientific knowledge and the views implicit in the teaching and learning activities deployed, or made explicit in NOS teaching, create problems that are equally serious and potentially damaging. Furthermore, students’ NOS views may be particularly robust and resistant to change because they are constantly reinforced by powerful out-of-school experiences. Books, newspapers, television programmes, movies, advertisements, museum exhibits and Internet Websites are all likely to carry messages about science and images of scientists, and it is inevitable that students will be impacted by them.

If science teachers are to intervene effectively and shift students’ understanding about science in the desired direction, they need reliable information about
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students’ likely understanding of NOS issues and, when possible, how their views develop over time and in response to particular kinds of interventions. If we can identify the kind of experiences that stimulate change and development we are in a much stronger position to design effective curricula for achieving critical scientific literacy. Teacher educators and curriculum developers also need to know about teachers’ NOS views and how they influence curriculum decision-making and, thereby, impact on students’ views. This has been a fruitful area of research in recent years, though it is fair to say that much more remains to be done. My intention here is not to provide an exhaustive review of the literature; that task has already been admirably carried out by Lederman (1992, 2007) and Abd-El-Khalick and Lederman (2000). Rather, my purpose is to engage in critical reflection on this vast literature with a view to identifying some findings that are particularly relevant to the themes developed and elaborated throughout this book, findings that may provide some guidance on curriculum structure, design of teaching and learning activities, development of curriculum materials, appropriate NOS-oriented programmes for preservice teacher education and priorities for continuing teacher professional development.

RESEARCH METHODS

Methods for ascertaining students’ and/or teachers’ views about science and scientists include questionnaires and surveys, interviews, small group discussions, writing tasks and classroom observations (particularly in the context of hands-on activities). As discussed below, each has its strengths and weaknesses. Necessarily, researchers who use questionnaire methods decide what should count as legitimate research data before the data collection process begins; those who use classroom observation (and, to a lesser extent, those who use interview methods) are able to make such decisions after data collection. They also have the luxury of embracing multiple perspectives.

Among the best-known NOS-oriented questionnaires are the Test on Understanding Science (TOUS) (Cooley & Klopfer, 1961), the Nature of Science Scale (NOSS) (Kimball, 1967), the Nature of Science Test (NOST) (Billeh & Hasan, 1975) and the Nature of Scientific Knowledge Scale (NSKS) (Rubba, 1976; Rubba & Anderson, 1978), together with a modified version (M-NSKS) developed by Meichtry (1992). Instruments dealing with the processes of science, such as the Science Process Inventory (SPI) (Welch, 1969a), the Wisconsin Inventory of Science Processes (WISP) (Welch, 1969b) and the Test of Integrated Process Skills (TIPS) (Dillashaw & Okey, 1980; Burns et al., 1985) could also be regarded as providing information on understanding some key aspects of the nature of science. While questionnaires are quick and easy to administer, they can be overly restrictive, incapable of accommodating subtle shades of meaning and susceptible to misinterpretation. Only very rarely do they afford respondents the opportunity to explain why they have made a particular response to a questionnaire item. It may well be that the same response from two respondents arises from quite different
understanding and reasoning, while similar reasoning by two respondents may result in different responses.

As pointed out in Hodson (2008, chapter 2), most of the early instruments were constructed in accordance with a particular philosophical position and are predicated on the assumption that all scientists behave in the same way. Hence teacher and/or student responses that do not correspond to the model of science assumed in the test are judged to be “incorrect”, “inadequate” or “naïve”. Lucas (1975), Koulaidis and Ogborn (1995), Alters (1997) and Lederman et al. (2002) provide an extended discussion of this issue. It is also the case that many of these instruments pre-date significant work in the philosophy and sociology of science, and so are of severely limited value in further studies. Like research in science itself, research in science education is a product of its time and place, and there is a constant need to update its methods. Reviews by Lederman (1992, 2007) and Lederman et al. (1998, 2000) describe several additional NOS instruments that take into account the work of more recent and even contemporary scholars in philosophy and sociology of science. Most notable among these newer instruments are Conceptions of Scientific Theories Test (COST) (Cotham & Smith, 1981), Views on Science-Technology-Society (VOSTS) (Aikenhead et al., 1989), the Nature of Science Survey (Lederman & O’Malley, 1990), and the Views of Nature of Science Questionnaire (VNOS) (Lederman et al., 2002) and its several subsequent modifications (see Lederman, 2007).

Sometimes the complexity and subtlety of NOS issues makes it difficult to find appropriate language for framing questions. Opinions in philosophy of science are rarely of the kind that can be readily expressed in short statements with which all individuals can confidently and unambiguously agree or disagree. If it is difficult for the researcher to find the right words, how much more difficult is it for the respondent to capture the meaning they seek to convey? In consequence, it cannot be assumed that the question and/or the answer will be understood in exactly the way it was intended, especially with younger students and those with poor language skills. Far from solving these problems, multiple-choice items can sometimes exacerbate them by leaving no scope for expressing doubt or subtle shades of difference in meaning. One response is to administer the questionnaire orally or to adopt an interview-based approach.

Despite some interesting recent developments in questionnaire design, one problem remains unsolved: students do not always interpret questionnaire items in the way the designers intended. The designers of VOSTS attempted to circumvent this problem by using multiple choice items derived from student writing and interviews to provide a number of different “position statements” (sometimes up to 10 positions per item), including “I don’t understand” and “I don’t know enough about this subject to make a choice” (Aikenhead et al., 1987; Aikenhead & Ryan, 1992). It is the avoidance of the forced choice and the wide range of aspects covered (definitions, influence of society on science/technology, influence of science/technology on society, characteristics of scientists, social construction of scientific knowledge, social construction of technology, and nature of scientific knowledge) that give the instrument such
enormous research potential. Nevertheless, as Abd-El-Khalick and BouJaoude (1997) and Botton and Brown (1998) point out, VOSTS was conceived and written within a North American sociocultural context and, in consequence, may have limited validity in non-Western contexts. In response to concerns like these, Tsai and Liu (2005) have developed a survey instrument that they claim is more sensitive to sociocultural influences on science and students’ views of science. It focuses on five characteristics of scientific knowledge and its development: (i) the role of social negotiations within the scientific community; (ii) the invented and creative nature of science; (iii) the theory-laden nature of scientific investigation; (iv) the cultural influences on science; and (v) the changing and tentative nature of scientific knowledge. Rooted in similar concerns about the socioculturally-determined dimensions of NOS understanding is the Thinking about Science instrument designed by Cobern and Loving (2002) as both a pedagogical tool (for preservice teacher education programmes) and a research tool for assessing views of science in relation to economics, the environment, religion, aesthetics, race and gender.

Lederman and O’Malley (1990) utilized some of the design characteristics of VOSTS to develop an instrument comprising just seven fairly open-ended items (e.g., “Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer”), to be used in conjunction with follow-up interviews. Not all students were prompted to focus their answers on the tentativeness of science, as the authors intended, and although the interview stage was able to go some way towards re-focusing attention, these findings serve to reiterate the difficulty of attempting to interpret students’ understanding from their written responses to researcher-generated questions.1 Because of differences in underlying philosophical position, and the likely low correlation between scores obtained using different instruments, questionnaire data obtained from different student or teacher populations should only be used for comparative purposes if the same instrument is used throughout, and even then the specific limitations and biases of the instrument should be clearly acknowledged.

Frustrated by these problems, some researchers and teachers incline to the view that more useful information can be obtained, especially from younger students, by relying solely on open-ended methods such as the Draw-a-Scientist Test (DAST) (Chambers, 1983). In his initial study, Chambers used this test with 4807 primary (elementary) school children in Australia, Canada and the United States. He identified seven common features in their drawings, in addition to the almost universal representation of the scientist as a man: laboratory overall; spectacles (glasses); facial hair; “symbols of research” (specialized instruments and equipment); “symbols of knowledge” (books, filing cabinets, etc); technological products (rockets, medicines, machines); and captions such as “Eureka” (with its attendant lighted bulb), E=mc² and think bubbles saying “I’ve got it” or “A-ah! So that’s how it is”. In the 25 years since Chambers’ original work, students’ drawings have changed very little (Fort & Varney, 1989; Symington & Spurling, 1990; Mason et al., 1991; Jackson, 1992; Newton & Newton, 1992, 1998; Rosenthal, 1993; Matthews, 1994; Huber & Burton, 1995; She, 1995, 1998;
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Rahm & Charbonneau, 1997; Barman, 1997, 1999; Finson, 2002; Fung, 2002), with research indicating that the stereotype emerges round about grade 2 and is well-established and held by the majority of students by grade 5.

When Losh et al. (2008) invited 70 students in grade 1, 58 students in grade 2 and 78 in grade 3 to draw a teacher and a veterinarian (“animal doctor” was the term used) as well as a scientist, 70% of the teachers were recognizably female, 53% of animal doctors were recognizably female and 60% of the scientists were recognizable male. Ambiguous gender figures were fairly common among grade 1 boys (28% for scientists, 31% for teachers and 48% for veterinarians), leading the researchers to speculate that other researchers had provided clear instructions on gender assignment. Fung (2002) also notes a high incidence (22%) of gender ambiguity among the drawings of 675 Hong Kong students in grades 2, 4, 6, 8 and 10. Despite their more regular exposure to teachers than to the other occupations, students in the Losh et al. (2008) study drew fewer details for teachers, providing more beakers, lab coats or animals for scientists or veterinarians than they drew chalkboards, books or pencils for teachers. Scientists smiled less and were seen as less attractive overall than teachers and veterinarians.

However, there is a strong possibility that researchers can be seriously misled by the drawings children produce. As Newton and Newton (1998) point out, “their drawings reflect their stage of development and some attributes may have no particular significance for a child but may be given undue significance by an adult interpreting them” (p. 1138). Even though young children invariably draw scientists as bald men with smiling faces, regardless of the specific context in which the scientist is placed (except in the study described above), it would be unwise to assume that children view scientists as especially likely to be bald and contented. As Claxton (1990) reminds us, children compartmentalize their knowledge and so may hold several images of the scientist – for example, the everyday comic book or cartoon version, the “official”, approved curriculum version for use in school, and their personal (and perhaps private) view. It is not always clear which version DAST is accessing, nor how seriously the student took the drawing task. Simply asking students to “draw a scientist” might send them a message that a “typical scientist” exists (Boylan et al., 1992). There is also the possibility, especially with students in upper secondary school or university, that the response is intended to make a sociopolitical point – for example, that there are too few women or members of ethnic minority groups engaged in science. Scherz and Oren (2006) argue that asking students to draw the scientist’s workplace can be helpful, while Rennie and Jarvis (1995a) suggest that students should be encouraged to annotate their drawings in order to clarify meaning and intention. Further insight into students’ views can be gained by talking to them about their drawings and the thinking behind them, asking them if they know anyone who uses science in their work (and what this entails), or presenting them with writing tasks based on scientists and scientific discovery. Miller (1992, 1993) advocates the following approach: “Please tell me, in your own words, what does it mean to study something scientifically?” When given the opportunity to discuss their drawings and stories with the teacher, even very young children will
provide detailed explanations (Sumrall, 1995; Sharkawy, 2006; Tucker-Raymond et al., 2007). Interestingly, discussion seems to take a different course when this task is set in science lessons than it does in other areas of the curriculum. It is also increasingly evident that young children’s responses to open-ended writing tasks involving science, scientists and engineers are not stable and consistent: accounts and stories produced in science lessons are very different from those produced in language arts lessons (Hodson, 1993a). Students may even provide significantly different oral and written responses to nature of science questions (Roth & Roychoudhury, 1994).

While less restrictive, instruments designed for more flexible and open-ended responses, such as the Images of Science Probe (Driver et al., 1996), small group discussion and situated-inquiry interviews (Welzel & Roth, 1998; Ryder et al., 1999), sometimes pose major problems of interpretation for the researcher. So, too, do observation studies, unless supported by an interview-based follow-up capable of exploring the impact of context on student understanding. While interviews hold out the possibility of accessing underlying beliefs, their effectiveness can be severely compromised by the asymmetric power relationship between interviewer and interviewee, regardless of whether the interviewer is the teacher or an independent researcher. In an interview situation, some students may be shy or reluctant to talk; they may feel anxious or afraid; they may respond in ways that they perceive to be acceptable to the interviewer, or expected by them. Observation via audio or video recording of group-based tasks involving reading, writing and talking, practical work, role play, debating and drama constitute a less threatening situation for students, though even here there can be problems. Any classroom activity can be impacted by complex and sometimes unpredictable social factors. Indeed, it would be surprising if activities taking place in the very public venues of classrooms were not influenced by the social goals of students: making friends, feeling comfortable, impressing others, “attending to their image”, and so on. Students carrying out activities in school science classrooms are not “free agents”, no more than scientists doing science in their laboratories are free agents. Both are constrained by and driven by social pressures and social aspirations. Both sets of activities take place in spaces where image, reputation, power and prestige play a very significant role, spaces where social skills are crucial and awareness of social norms is crucial. As in science itself, authority and prestige can play an important role in the classroom, especially in group-work situations, with the views of the most insistent or the most prestigious group members being likely to prevail. All who have had dealings with adolescents (especially their own children) are uncomfortably aware of the power of peer group influences and the drive towards conformity with the group’s norms, rules, language, dress and behaviour, and the stress induced by failure to gain admission to the valued group. The point is that the ways in which a group engages in classroom activities depends on the nature of the social interactions within the group to an extent at least equal to its dependence on the students’ cognitive understanding of what is required of them. These complicating factors can mask or distort the NOS understanding we hope to infer from conversations and actions. In short, all approaches
to ascertaining NOS views carry a risk that the characterization or description of science ascribed to the research subject is, in some measure, an artifact of the research method.

The context in which an interview question, questionnaire item or assessment task is set and, indeed, whether there is a specific context at all, can have major impact on an individual’s response. Decontextualized questions (such as “What is your view of a scientific theory?” or “What is an experiment?”) can seem infuriatingly vague to students and can be met with seeming incomprehension. Use of such questions can pose major problems of interpretation for the researcher. Conversely, context-embedded questions have domain specific knowledge requirements that may sometimes preclude students from formulating a response that properly reflects their NOS views. Moreover, respondents may feel constrained by restriction of the question to one context and unable to communicate what they know about the many significant differences in the ways that scientists in different fields conduct investigations. Familiarity with the context, understanding of the underlying science concepts, interest in the situation, and opportunity to utilize knowledge about other situations, are all crucial to ensuring that we access the students’ authentic NOS understanding. Put simply, questions set in one context may trigger different responses from essentially the same questions set in a different context. To shed more light on this issue, Leach et al. (2000) conducted a study of 731 science students at upper secondary and undergraduate level in five European countries. Participating students were asked to respond to two groups of questions: first, some generalized, context-free items such as “Rate your agreement/disagreement with the two statements ‘one data set always leads to one conclusion’ versus ‘different conclusions can legitimately be drawn from the same data’ on a scale of 1–5”; second, a series of questions embedded in a specific subject context. Data analysis revealed three distinctive forms of reasoning: (i) data focused reasoning – scientific knowledge is a description of the material world, with differences of interpretation capable of being resolved by collecting further data; (ii) radical relativist reasoning – data cannot be used to determine whether a view is correct or incorrect, individuals are free to interpret observational and experimental data as they see fit; (iii) theory and data related reasoning – what scientists believe, what they do during investigations and what data are collected are closely inter-related, each being capable of influencing the others. The authors conclude that there is no evidence to indicate that a student’s responses to generalized questions can be used to predict the way they are likely to respond to questions in a specific context. Nor is there any evidence to suggest that students hold unique epistemological positions that they use across a wide range of contexts. Consequently, if questions and tasks are to be set in specific contexts there are important decisions to be made between school science contexts and real world contexts. This is especially important in research that addresses NOS views in the context of socioscientific issues (Sadler & Zeidler, 2004) and scientific controversies (Smith & Wenk, 2006).

It would be surprising if students did not have different views about the way science is conducted in school and the way science is conducted in specialist
research establishments. Hogan (2000) refers to these different views as students’ 
*proximal* knowledge of NOS (personal understanding and beliefs about their own
 science learning and the scientific knowledge they encounter and develop in sci-
 ence lessons) and *distal* knowledge of NOS (views they hold about the products,
 practices, codes of behaviour, standards and modes of communication of profes-
 sional scientists). Sandoval (2005) draws a similar distinction between students’ 
*practical* and *formal* epistemologies. Contextualized questions that ask students
 to reflect on their own laboratory experiences are likely to elicit the former, ques-
 tions of a more general, de-contextualized nature (“What is science?” or “How do 
scientists validate knowledge claims?”) are likely to elicit the latter. The problem 
for the researcher is to gauge the extent to which these differences exist and how 
they are accessed by different research probes. The problem for the teacher is to 
close the gap or, more in line with the arguments running through this book, to 
ensure that students are aware of the crucial distinctions as well as the similarities 
between science in school and science in the world outside school.

It almost goes without saying that there is significant potential for mismatch 
between what individuals state about their NOS understanding and what they do 
in terms of acting on that understanding, and this applies just as much to teachers 
as it does to students. Thus, another crucial consideration is whether we seek to 
ascertain espoused views or views implicit in actions. The former would probably 
be best served by questionnaires, writing tasks and interviews; the latter requires 
inferences to be drawn from observed behaviours and actions. It may also be the 
case that students hold significantly different views of science as they perceive 
it to be and science as they believe it should be – a distinction that Rowell and 
Cawthron (1982) were able to accommodate in their approach.

If we solve all these problems, we are still confronted with decisions about 
how to interpret the data. Should we adopt a nomothetic approach that focuses 
on the extent to which the students’ or teachers’ views match a pre-specified 
“ideal” or approved view? Any attempt to distinguish “adequate” NOS views from 
“inadequate” views involves judgements about the rival merits of inductivism and 
 falsificationism, Kuhnian views versus Popperian views, realism versus instru-
 mentalism, and so on. None of these judgements is easy to make, as discussion in 
Hodson (2008) has shown. Does it make more sense, then, to opt for an ideo-
 graphic approach? Should we be satisfied to describe the views expressed by 
students and seek to understand them “on their own terms”? A major complicating 
factor is that neither students nor teachers will necessarily have coherent 
and consistent views across the range of issues embedded in the notion of NOS.
 Rather, their views may show the influence of several different, and possibly 
mutually incompatible philosophical positions. Older students, with more so-
phticated NOS understanding, will have recognized that inquiry methods vary 
between science disciplines and that the nature of knowledge statements varies 
substantially with content, context and purpose. Few research instruments are 
sensitive to such matters. By assigning total scores rather than generating a profile 
of views, the research conflates valuable data that could inform the design of 
curriculum interventions. Rather than assigning individuals to one of several pre-
determined philosophical positions, it might make more sense to refer to their *Personal Framework of NOS Understanding*, and seek to highlight its interesting and significant features, an undertaking that could be facilitated by the use of repertory grids (as in the study by Shapiro, 1996). Although Abd-El-Khalick (2004) found substantial inconsistencies in the NOS views of students at the undergraduate and graduate levels, he acknowledges that inconsistencies from the researchers’ point of view may still be seen by the students as “a collection of ideas that make sense within a set of varied and personalized images of science” (p. 418).

A recent study by Ibrahim et al. (2009) does seek to consolidate data from a purpose-built questionnaire into NOS profiles. The questionnaire, *Views about Scientific Measurement* (VASM), which comprises six items addressing aspects of NOS and eight items dealing with scientific measurement, uses a common context (in earth sciences) and allows space for students to elaborate on their response or compose an alternative. The data, obtained from 179 science undergraduates, were found to cluster into four partially overlapping profiles: *modellers*, *experimenters*, *examiners* and *discoverers*. For modellers, theories are simple ways of explaining the often complex behaviour of nature; they are constructed by scientists and tested, validated and revised through experimentation. Creativity plays an important role in constructing hypotheses and theories, and in experimentation. When there are discrepancies between theoretical and experimental results, both theory and the experimental data need to be scrutinized. Experimenters also believe that scientists should use experimental evidence to test hypotheses and theories, but should do so in accordance with a strict scientific method. In situations of conflict, data have precedence over theories. Examiners regard the laws of nature as fixed and “out there” waiting to be discovered through observation, rather than constructed by scientists. Experimental work is essential; it is not informed by theory. Scientists may use both the scientific method and their imagination, but experimental data always have precedence over theories. Discoverers also believe that the laws of nature are out there waiting to be discovered through observation. Only experiments using the scientific method can be used to generate laws and theories. If experimental data conflict with a previously established theory, then both the theory and the data need to be checked. Interestingly, as a percentage of the total, the modeller profile was more common among students following a 4-year science foundation course than among physics majors.

Of course, different researchers make different decisions on these crucial questions. Sadly, however, not all researchers are appreciative of the consequences of the decisions they make for the validity, reliability and usefulness of the data they generate, though perhaps they are no more guilty in this respect than are researchers in other fields. Perhaps, as in many other situations, the most prudent approach is to use a range of methods and, of course, to subject all methods to close critical scrutiny, preferably by a team of evaluators with wide and varied experience. Despite the many caveats concerning the validity and reliability of research methods, it is incumbent on teachers, teacher educators and curriculum
developers to pay careful attention to the findings of the rapidly growing number of studies that focus on students’ and/or teachers’ NOS views. For convenience, I have chosen to look separately (though only briefly) at students’ views and teachers’ views, with some “free floating” remarks concerning scientists’ views.

STUDENTS’ VIEWS OF SCIENCE AND SCIENTIFIC INQUIRY

It is always dangerous to generalize from research findings. Nevertheless, there seems to be a widespread view among students that science is an elitist activity, out of the reach of ordinary people, and that scientists are exceptionally smart and hard-working individuals, whose overriding goal is the betterment of life in general. Aikenhead et al. (1987) report that most students regard scientists as being motivated by curiosity (the need to “find out how things are”) and the desire to “make the world a better place to live in”, attributing these motives to scientists ahead of “earning a good salary” or “becoming famous”. In terms of personal attributes, Ryan (1987) reports that scientists are generally seen by students as honest, trustworthy, objective, logical, methodical, analytical, and open-minded.  

It is fairly common for students to assess scientists very positively in terms of cognitive abilities, while being less complimentary with regard to their personality traits, social skills, and moral-ethical standards (Ward, 1986; Andre et al., 1999; Song & Kim, 1999; Carlone, 2004). While they are respected for their expertise, scientists are often seen as drab, uninteresting, introverted, unemotional, insensitive, socially inept, “nerdy”, work-obsessed individuals who are sometimes highly secretive and occasionally sinister and dangerous. Scientists have few interests, and certainly not in music, movies, or the arts in general. Most scientists do not have a “normal” family life: they may neglect their family or do not have a family because of their preoccupation with work. Indeed, they often go into the laboratory on their day off, working long hours on problems that have little relevance to people or social issues. Often, they are seen as careless of their appearance, generally untidy and disorganized; sometimes they even forget to eat because of their obsession with work. There is some evidence that stereotyped views relating to social issues are held more strongly by girls than by boys (Miller et al., 2006). Oddly, there is some evidence that the views of students whom Costa (1995) would characterize as “potential scientists” seem to hold particularly stereotyped views in this respect, views that are often surprisingly resistant to change. At the student teacher level, this situation seems to be reversed: those intending to teach science, presumably those with greater exposure to science and scientists, include fewer stereotypical features in their drawings of scientists than do those specializing in the liberal arts (Rosenthal, 1993). It almost goes without saying that an unfavourable image of scientists in respect of personal characteristics is bad for recruitment. As Sheffield (1997) comments, “Ask any teenager, or even any preteen, what she or he thinks that students gifted in mathematics and science look like, and it is likely that the answer will include an image that looks like the ‘nerdy’ scientist from Back to the Future: male, with glasses, a pocket protector,
and a very strange hairdo … It is nearly impossible to encourage students to do well in mathematics and science when they are faced with such ridiculous stereotypes everywhere they turn” (pp. 377 & 378, cited by Painter et al., 2006, p. 182). It is also bad for public confidence in science, and is likely to weaken political support for research and development.

If, for whatever reason, people dislike the stereotypical scientists, they are less likely to support science. Why subsidize geeks to pursue their absurd and incomprehensible little projects? (Sagan, 1995, p. 363)

Reis and Galvão (2007) report on the ways in which the plots of science fiction stories written by students (in this case, by grade 11 students) can tell us a great deal about their perceptions of science and scientists. The authors note that some of the stories reveal the influence of the stereotypes and “catastrophic scenarios” depicted in movies, TV shows, books, comics and cartoons, including “the scientist as the hero and savior of society; the dangerous, ruthless scientist working on secret, controversial projects; and the scientist incapable of controlling the result of his work” (p. 1257). Follow-up interviews provide a valuable opportunity to challenge and possibly correct mistaken and stereotyped ideas about science, scientists and scientific practice.

There is some evidence (e.g., Barman, 1999) that students, at least in some parts of the world, are beginning to view scientists in a more “realistic way” – that is, as regular people rather than all-knowing geniuses, madmen, geeks or freaks. There is evidence that stereotypes weaken somewhat as students get older, possibly in response to the ways in which science is presented in school (She, 1998). Indeed, there is encouraging evidence that students’ views can be favourably impacted by carefully designed interventions, especially those that focus on gender, ethnicity and physical disability (Flick, 1990; Bodzin & Gehringer, 2001; Bohrmann & Akerson, 2001; Sharkawy, 2006). However, Mbajiorgu and Iloputaife (2001) report that while an adapted VOSTS questionnaire and use of DAST indicated that the image of scientists held by preservice teachers had been favourably impacted by an NOS-oriented lecture programme, especially with respect to gender stereotyping, the changes seemed to be restricted to espoused views communicated during the research, and were unlikely to have significant influence on classroom or out-of-school behaviour. In one sense, this mirrors Hogan’s (2000) observation of the disconnect or mismatch that often exists between students’ understanding of the ways in which scientific knowledge is constructed and their understanding of how they themselves acquire new scientific knowledge.

It is probably fair to say that most students see science as being concerned with addressing natural phenomena through empirical investigations. Younger students see science as proceeding largely as an inductive process: making discoveries or “finding out things” through prolonged, careful and systematic observation. Older students often see science as a process of hypothesis testing. Generally, students regard observational evidence, especially that produced by experiment, as constituting the only legitimate support for a theory. There is little understanding
that some theories (such as evolutionary theory or theories in plate tectonics, for example) are based on historical evidence (the fossil record), argument, and in recent years, perspectives developed through computer simulation. It is still common for students to believe that science is restricted to laboratory settings, and, as would be expected, “experiments” figure prominently in almost all students’ descriptions of what scientists do. For many young children, an experiment is any practical activity, including measuring things or mixing things together in order to “see what happens”, “make something happen” or “do something new” – a complex of views that probably reflects the tendency of teachers to refer to all hands-on activities as “experiments”. As they gain more experience, students come to regard experiments as a reliable means of “finding out what actually happens”, seeking a cause (of the effect they observe) or testing a prediction (usually to confirm it), provided that they are designed and conducted in accordance with the requirements of “the scientific method”. It is commonly believed that careful adherence to the designated steps of this method is what gives scientists confidence in the knowledge the method generates.

The 12 year olds in the study conducted by Carey et al. (1989) are typical of many younger students in not regarding experiments as being guided by ideas, questions and assumptions. Indeed, the idea that experiments and other empirical investigations are conducted as part of the theory-building process in order to compile evidence for checking, testing and developing hypotheses and models, develops very slowly, and sometimes not at all (Driver et al., 1996). Because of the way practical work in school is organized, particularly with respect to writing a mandated and formulaic lab report, most students see experimental inquiry as a straightforward linear sequence of planning, conducting, interpreting and reporting. There is little appreciation of the reflexive nature of experimental design, little recognition that scientists frequently have to engage in revision and reorientation of the procedures in order to overcome initial shortcomings in design. In general, students are unaware that the scientific knowledge generated by experiments is provisional and subject to further critical scrutiny (Carey & Smith, 1993). It is particularly disturbing that all 11 science undergraduates in the study by Ryder et al. (1999) subscribed to the view that scientific knowledge can be proved beyond doubt by collecting appropriate empirical data. While this is a worrying enough view for future scientists to hold, it is considerably more worrying (in the context of this book’s position on critical scientific literacy) when it is held by future teachers, physicians, journalists and politicians.

Using a questionnaire-based approach, Pomeroy (1993) found that scientists were more likely than science teachers to express traditional empiricist views about science. However, interviews with scientists often reveal a somewhat different picture. In the study conducted by Wong and Hodson (2009), all the scientists expressed the view that the specific approach to an inquiry is dependent on the nature of the problem, the knowledge we already possess, the personnel and technical facilities available, and so on. There is no one method! Although the scientists interviewed by Schwartz and Lederman (2006) noted that scientific investigation and theory building proceed in diverse ways, depending on the field,
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there was a clear indication by some (9 out of 24) that “claims made through experimental methods were more valid than claims made through non-experimental methods” (p. 13). Interestingly, one of the scientists in the Wong and Hodson (2009) study remarked that although controlled experiments constitute a particularly powerful means of establishing the validity of knowledge claims, no one experimental design can ensure perfectly valid and reliable data. Not only can small variations in method sometimes produce large differences in data, but seemingly identical procedures can produce different data because of differences in the quality of the instruments and the craft skills of the technicians. Discussion in both studies turned, as is usual in conversations with scientists about their methods, to the question of whether investigations need to be hypothesis-driven. In Schwartz and Lederman’s (2006) study, chemists and life scientists said “Yes”, while earth scientists and physicists said “No”. Again, context seems to be the crucial consideration. One of the scientists interviewed by Wong and Hodson (2009) said that although investigations are not always hypothesis-driven, particularly in molecular biology (the scientist’s own area of expertise), it is important to pretend that they are when submitting proposals for funding because funding agencies expect it and regard open-ended inquiries as little more than “fishing expeditions”. A number of scientists reported that hypotheses are no longer necessary in many areas of study because recent advances in technology enable enormous amounts of data to be collected and analyzed in a matter of minutes. Interesting issues and problems for systematic study emerge by a process of “data mining”. The research chemists interviewed by Samarapungavan et al. (2006) described their work in terms of trying to build molecules that theory suggests are possible, rather than in terms of testing a hypothesis or theory. Failure to synthesize the molecule is not seen as falsification of the underlying theory so much as a stimulus to greater effort in finding a suitable route. While this study is important in highlighting how scientists in different disciplines use substantially different approaches to inquiry, it does seem to make the assumption that all research in chemistry is necessarily focused on synthesis. Although the authors report no data to that effect, it is reasonable to assume that sub-disciplines within chemistry will have their own distinctive and context-specific methods. Interestingly, Schwartz and Lederman (2008) report that differences in investigative approaches among the 24 scientists in their research sample are not illustrative of distinctive features of the broader sub-disciplines of chemistry, physics, biology and earth sciences; rather, they seem to arise from specific individual contexts and experiences.

When asked how they evaluate the quality of their work, the chemists interviewed by Samarapungavan et al. (2006) mentioned design criteria (such as elegance, efficiency and percentage yield), the judgement of others (via peer review, successful publication, level of research funding), the impact and fruitfulness of their work (both within the community and the wider society) and what the authors refer to as “cognitive factors”: namely, “novelty, difficulty and completeness of the work” (p. 484). Students, however, rarely mentioned any criterion for judging the quality of research other than empirical adequacy. When Glasson and Bentley (2000) interviewed four scientists and two engineers, as part of a con-
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ference designed to acquaint science teachers with current research practice, all the scientists emphasized the importance of research design in obtaining valid and reliable data, though they noted that what constitutes good design is contingent on the specific circumstances of the inquiry. While both scientists and engineers made reference to connections between their research and societal issues (e.g., developing drugs to fight cancer, increasing agricultural production, etc.), the authors noted a tacit underlying assumption that science is free of bias and vested interest, and proceeds in a value-free and ethically neutral way.

SCIENTIFIC REASONING AND SCIENTIFIC KNOWLEDGE

There is evidence that many students perform less than satisfactorily in designing scientific investigations and interpreting data. Often they fail to generate or test hypotheses (on the occasions hypotheses are required), ignore critical variables, and interpret data in a way that supports prior beliefs. Kuhn et al. (1988) argue that scientifically literate people possess a set of “domain general” (i.e., generalizable and transferable) thinking skills that enable them to coordinate theory and evidence. Thus, they can consciously articulate the theories they hold, state what evidence supports or would refute them, and can justify why they hold a particular view, rather than some other view that might also explain the evidence. This set of abilities constitutes a major element in my notion of critical scientific literacy, as discussed in Chapter 1. Their research seems to show that these abilities develop slowly and steadily over time. Indeed, Kuhn (1997) states that until early adolescence, children tend not to think of theory and evidence as separate. If she is correct, the weaknesses in scientific reasoning listed above are a consequence of students’ failure to recognize that their current beliefs can (and maybe should) be modified in the light of evidence. When people think only with their theories rather than about them, say Kuhn et al. (1988, 1995), they are unable to consider alternatives. Further, these authors say, it is only by considering alternatives, and seeking to identify “what is not”, that one can begin to achieve confidence in one’s knowledge of “what is”.

Two issues are relevant to consideration of Kuhn’s conclusions. First, the propositions with which the research subjects are presented seem to grossly misrepresent the nature of scientific theory; second, the activities in which Kuhn and her co-workers ask students to engage bear little resemblance to real scientific inquiry. For example, it is difficult to see how studying some fairly trivial data with a view to choosing the more likely of some possible causes, such as whether the smoothness of a tennis ball affects a player’s service (or not) or whether apples or oranges are better at warding off a cold (Kuhn et al., 1988), can be regarded as an exploration of the applicability and robustness of a scientific theory. Similar doubts focus on the researchers’ use of an exercise in manipulating variables that might affect the speed of a toy boat or toy car (Kuhn et al., 1995). Much more convincing is Samarapungavan’s (1992) finding that the ability to use a theory and argue for its appropriateness (in terms of consistency with the evidence)
is largely a matter of familiarity with the particular concepts involved. In other words, effective theory use constitutes a set of “domain specific” reasoning skills (see also Brown, 1990; Koslowski, 1996). When students have this familiarity and have interest in the situation or phenomenon under consideration, Samarak unpugavan (1992) argues, children as young as six are able to differentiate theories on grounds of logical and empirical consistency, generalizability, parsimony and scope. Similarly, Sodian et al. (1991) found that grade 1 and grade 2 students can distinguish belief from evidence, and can recognize disconfirming evidence when the situation does not make high-level knowledge demands or present a major conflict with students’ prior beliefs. Schauble et al. (1991a, 1995) and Schauble (1996) have also pointed out the crucial role played by conceptual knowledge. Put simply, students can reason better when they have a rich conceptual background on which to draw and, thereby, are better positioned to investigate more thoroughly and systematically (see also, Dunbar, 1993). When students have only rudimentary conceptual understanding it is difficult for teachers and researchers to ascertain whether a poorly constructed explanation or argument is a consequence of lack of understanding of the content or lack of understanding of the nature of scientific explanations. It is also the case that scientific reasoning is not simple common sense; rather, it is part of a cultural tradition and its characteristics have, to an extent, to be learned (Brewer & Samarapungavan, 1991). Developing expertise in scientific reasoning is a process of “bootstrapping” between conceptual/theoretical knowledge and careful consideration of evidence: considerations of theory constrain data collection and interpretation, and the data constrain, refine and elaborate theory. Confirmation of the centrality of conceptual understanding can be found in Kuhn’s (2007) observation that students who have successfully distinguished between causal and non-causal variables in one context cannot always utilize that understanding successfully in a different context. Further elaboration of the continuing dispute between advocates of domain-general and domain-specific arguments is outside the scope of this book. Kuhn and Pearsall (2000), Metz (2000, 2004), Zimmerman (2000), Lehrer and Schauble (2006) and Schauble (2008) provide much useful research data and background theorizing relevant to the dispute.

Driver et al. (1996) characterize students’ reasoning about theory and evidence in terms of whether it is phenomenon-based, relation-based or model-based. In phenomenon-based reasoning, an approach used only by the youngest students in the research sample (12 year olds), a theory is a taken-for-granted statement of fact, and no distinction is made between observations and explanation. Explanations are simply a re-statement of the observations, and investigations of phenomena are largely random or ad hoc. In relation-based reasoning (the commonest form of reasoning among 12 and 16 year olds), a distinction is made between observation and explanation. Commonly, the explanation is a generalization from empirical data or a correlation between stated variables arrived at by inductive reasoning and expressed in the same kind of language categories as the observations, but with no reference to any underlying mechanism. In model-based reasoning (used by only a minority of students, even at age 16) there is a
discontinuity between explanation and observations. Explanations involve posited entities, couched in different language from the observations (for example, the macro behaviour of substances explained in terms of atoms and molecules), and are clearly the outcome of creative endeavour by scientists. Observational evidence constitutes a reason for subscribing to a particular explanation or theory, and so the appearance of new evidence is an incentive to shift allegiance to a model that better deals with it. Although these categories form a clear hierarchy in terms of the complexity and sophistication of the reasoning, with model-based reasoning being the target learning, it seems that students who have reached the level of model-based reasoning in some subject areas may still revert to a less sophisticated approach on occasions, especially when unfamiliar with the associated concepts. They may also be disinclined to use this “higher level” approach when the context is of little interest or importance to them – clearly, an important message for all teachers. It is alarming that when Windschitl (2004) invited 14 preservice secondary school teachers to conduct an empirical investigation of their choice and design, none employed model-based reasoning. Following a longitudinal study of 15 primary school students in Western Australia, Tytler and Peterson (2004) conclude that the relation-based reasoning category is insufficiently refined to capture the nuances of different student reasoning patterns. They propose a narrower definition of the category and the insertion of an additional category, which they call concept-based reasoning.

− **Relation-based reasoning** – explanations involve the identification of relations between observable or taken-for-granted entities, rather than a search for an underlying cause; explanatory approaches tend to be confirmatory and uncritical; they emerge from the data in an unproblematic way.

− **Concept-based reasoning** – explanations are cast in terms of conceptual entities; experimentation is guided by hypotheses; the role of disconfirming evidence is acknowledged as significant.

The authors point out that their definition of relation-based reasoning has much in common with the engineering model of experimentation proposed by Schauble et al. (1991b), where “the purpose is seen as the achievement of a successful outcome rather than identification of cause, and where there is a focus on confirming and manipulating variables relevant to an outcome rather than test for disconfirming evidence” (p. 113).

Using a purpose-made instrument called Nature of Science Interview, which includes questions about the goals of science, the nature of scientific questions, the role of experiment, the theory-dependence of experiment and the processes by which scientists change their ideas, Carey and Smith (1993) have also characterized students’ epistemological understanding in terms of a 3-level hierarchy. At level 1, scientific knowledge is assumed to comprise a collection of true facts about the world, acquired in piecemeal and unproblematic fashion from observations and experiments. At this stage, no distinctions are made among scientists’ ideas, investigative approaches and findings; students have no appreciation of the role of scientists’ ideas in guiding their investigations, no notion that data from
investigation provides evidence for ideas, and no appreciation of the uncertainty and tentative nature of scientific knowledge. At level 2, scientific knowledge comprises a collection of tested ideas about “how things work” and “why things happen”; scientists design experiments involving measurements and observations in order to test their ideas, which they abandon or revise if the test does not confirm them. Students at this stage have developed the notions of explanation and hypothesis testing (though hypotheses are seen as data-generated rather than theory-generated) and are probably slightly ahead of students characterized as being at the “relation-based” stage in the Driver et al. (1996) model. At level 3, explanations are recognized as based on theoretical entities that are not part of the simple observation categories. Scientific knowledge comprises well-tested and coherent explanatory frameworks that scientists use to make predictions, construct specific hypotheses, design inquiries and interpret the evidence generated. Theories are recognized as inherently conjectural and hypothesis-driven, experiments are seen as a means of developing them further. Smith et al. (2000) have refined the coding system by introducing two intermediate levels. At level 1.5, there are signs of an awareness of the role of ideas in scientists’ work, although the nature of ideas is vague. At level 2.5, there is a deepening understanding of the conceptual/explanatory nature of hypotheses/theories, awareness that the same pattern of results can be interpreted in more than one way, and recognition that theories may be broader in scope than hypotheses and can affect hypothesis testing.

Carey and Smith (1993) found that Grade 7 students had average level scores of 1.0 across the various dimensions. In Honda’s (1994) study of Grade 11 students, cited by Smith et al. (2000, p.358), scores averaged at 1.39, although the majority of students reached level 2 on at least one dimension. In a study of 35 college freshmen intending to major in science, Smith and Wenk (2006) found that, in terms of differentiating between theory and evidence, students had average scores between 1.38 and 1.67, with most of their responses at level 1 or level 2; 12 students had average scores between 1.92 and 2.23, with most of their responses at level 2 or level 2.5; 13 students had average scores between 1.71 and 1.87, and were more evenly split between level 1.5 and level 2. Again, no student scored at level 3. Research showed that there was a strong relationship between students’ level of differentiation of scientists’ ideas and evidence, their awareness of the uncertainty and tentativeness of scientific knowledge, and their willingness to engage with scientific controversies.

No student with an average . . . score less than 1.7 (predominantly level 1 and 1.5) . . . regarded scientific knowledge as fundamentally uncertain . . . whereas almost all those with average . . . scores greater than 1.9 (consistent level 2 responders) did so. Those with average . . . scores between 1.7 and 1.9 were more variable, although the majority still regarded scientific knowledge as at least partially certain. Overall, there was a significant association between being a consistent level 2 responder . . . and being aware of the uncertainty of scientific knowledge . . . Similarly, there were clear relations between how students reasoned about a specific controversy . . . and their differentiation of
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evidence/hypotheses/theories ... and their understanding of the uncertainty of scientific knowledge ... For example, all students who systematically engaged with the controversy in deeper ways (e.g., by showing awareness that the scientists may have made interpretive errors) had been aware of the uncertainty of scientific knowledge. (Smith et al., 2000, p. 768)

Somewhat surprisingly, Thoermer and Sodian (2002) found no measurable differences between the scores of undergraduates studying science at a German university and those of graduate students in the same institution, though graduate students in physics did score substantially higher than all other groups.

CHANGE AND DEVELOPMENT

It would be surprising if students’ educational experiences did not impact their progress towards more sophisticated epistemological thinking. In an effort to test this supposition, Smith et al. (2000) studied two grade 6 classes with different educational histories. Both classes had been taught by one teacher only throughout grades 1 to 6. However, the teacher in one class had used a constructivist approach in which small groups of students investigated phenomena and developed personal models to explain them through experimentation and dialogue within and among groups, while the teacher of the comparison class had adopted a more traditional approach using lectures, readings, outdoor experiences and art work. The students in the constructivist class had developed more sophisticated views about the goals of science (with a shift away from “doing things” and “gathering information” towards “developing ideas and understanding”) and about the nature and purpose of experiments (a shift from “trying things out” and “finding answers” to “developing and testing ideas”). Indeed, 83% of students in the constructivist class had an average score of at least level 2, and all of them had average scores greater than 1.5 (see above, for an interpretation of these figures). In other words, they exhibited a level of sophistication usually only shown by students four or five grades more advanced. Indeed, the percentage of these grade 6 students expressing consistent level 2 views was higher than among the grade 11 students in Honda’s (1994) study. The students in the constructivist class were more aware of the tentative and evolving nature of scientific knowledge and of the complex nature of theory appraisal; they recognized scientists as reflective and creative individuals who often collaborate with others. A number of them noted that scientists’ current ideas probably influence what they choose to investigate, bias the design and interpretation of the inquiry, and cause them to resist new ideas preferred by others. Tucker-Raymond et al. (2007) report that a 10-week long course for 36 students in grades 1 to 3 involving extensive hands-on exploration, together with reading, writing and class discussion about science, brought about some significant shifts in students’ NOS understanding: what the researchers call the engineering view of science (scientists “make things”) decreased sharply, while the incidence of the “inductive-explorer view” and the “developing knowledge view” (scientists “find out things”) both increased sharply – a clear reflection of
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the curriculum experiences provided. Somewhat surprisingly, research by Liu and Tsai (2008) indicates that science majors among first-year undergraduates have less sophisticated beliefs regarding the theory-laden and culturally-dependent aspects of science than non-science majors. Disturbingly, science education majors (intending teachers) had the poorest scores overall. The authors speculate that science and science education majors have simply been exposed for much longer to a curriculum that presents scientific knowledge as objective and universal (see also Schommer & Walker, 1997; Paulsen & Wells, 1998; Hofer, 2000; Palmer & Marra, 2004; Smith & Wenk, 2006).

Hogan and Maglienti (2001) present an intriguing account of some key differences between scientists and grade 8 students in the ways they reason about data. The researchers provided each participant with a series of ten conclusions from data made by someone else (a fictitious biology teacher), nine of which had a weakness of some kind (such as not accounting for all of the data or using vague or unspecific language). In the context of a 1:1 interview they asked the participants to evaluate the validity of the ten conclusions. Scientists prioritized empirical consistency of evidence and conclusions, the need to consider all the evidence and the requirement that the argument be free of logical inconsistencies. Students put more emphasis on their own prior theoretical understanding and whether the conclusion matched their own inferences from the data. They tended to form their own conclusions from the data and then use it as a check on the conclusions they were asked to evaluate. Ford (1998) reports similar findings when scientists and non-scientists were asked about the confidence they had in the claims located in a series of three articles in a popular scientific magazine. Scientists considered how data were collected and analyzed; non-scientists used personal experience and conformity with their own views. Differences are also apparent in the way scientists and non-scientists ascribe cause and effect: non-scientists tend towards a few simplistic causal structures (best of all, one structure) into which all new data is assimilated; scientists are more willing to consider a range of options (Chi, 1992).

Other research has indicated that in situations where students collect their own data, and those data do not point clearly to a conclusion, students will often impose their own patterns on the data based on their prior expectations. Thus, Millar and Lubben (1996) report that in situations where the data are inconclusive, students draw conclusions in line with their predictions; when data are more clearly at variance with predictions, students respect the data if their prediction was merely a guess but distort data to meet the prediction if it was based on a well-understood theory about the phenomenon under investigation. In a related study with 11, 14 and 16 year olds, Lubben and Millar (1996) note that many of the younger students made observations and took measurements “with no apparent awareness of the uncertainty associated with the measurement process or of the need to be able to defend their data as reliable” (p. 956). Across the age groups there was evidence of a progression in understanding of both the processes of sound measurement (from denial of the need to repeat measurements, through a search for recurring results and deliberate manipulation of control variables to
ensure a satisfactory spread of results, to estimation of the likely range of results and identification of errors) and the evaluation of measurements (from assessing a single value on the basis of what is likely or expected, through selection in accordance with the place of the measurement in a sequence and selection of a recurring value, to using a full set to calculate mean or median). Studies of students’ responses to anomalous data conducted by Chinn and Brewer (1993, 1998), Chinn and Malhotra (2002a) and Lin (2007) reveal a marked reluctance to give it proper critical attention. Students may simply ignore it, reject it as irrelevant or outside the domain of the theory, cast doubt on its reliability and appropriateness, express concern about its proper interpretation, put it to one side for later consideration (which rarely occurs), or reinterpret it to make it consistent with their existing views. Only very rarely will they use it to reject or modify their existing theoretical views, and even then it is often no more than a peripheral change or minor modification. Toplis (2007) notes that the demands of school lab work, with its severe constraints on time, materials and apparatus, and the high priority placed on “correct answers” in conventional assessment schemes, militate strongly against students responding appropriately to anomalous data. Even if they recognize anomalies, and even if they might be willing to collect further data, they are rarely in a position to do so. Interestingly, Toth and Klahr (2001) found that students experienced fewer problems in reasoning successfully from anomalous empirical evidence when they had collected the data themselves than when data were provided by the teacher or taken from a textbook. It is important to recognize that within the scientific community the response to anomalous data is profoundly affected by the reputation of the scientists who generate it, whether the methods used to generate it are well-established, and whether the anomalous data can be replicated by other research groups.

Samarapungavan et al. (2006) report some interesting differences between students and scientists in their response to anomalous data. Scientists drew a distinction between routine methodological error due to calibration faults, impure reagents, lapses in bench technique, and the like, and “productive anomalies”, that is, unexpected results that are a stimulus to further investigation and theorizing. Undergraduates saw anomalous data as a clear indication of their own technical inadequacies, while high school students interpreted it as “getting the wrong result”. As all science teachers are aware, it is common for students at all levels of education to respond to this situation by “massaging the data” (changing their observations to match the expected conclusion), working backwards from the conclusion found in the textbook or on the Internet in order to generate “new data”, which is suitably adjusted so as not to seem “too good” or to “fit too well”. Alternatively, students simply obtain the “right results” from friends. Dunbar (1995) makes some interesting observations concerning the way inconsistent evidence is treated by scientists: less experienced scientists are more willing to maintain the hypothesis and reject the data than are more experienced scientists. While more experienced scientists show much less “confirmation bias” than their less experienced colleagues, they often display a “falsification bias”: discarding good
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In common with the students in several other studies, most of the 16 year olds interviewed by Driver et al. (1996) interpreted disagreements between scientists as evidence of sloppy work or incomplete data. Although some students did entertain the notion that personal interests and biases might impact the views of scientists, few students recognized that data can be interpreted in different ways because different theories are brought to bear.

Evidence seems to be regarded as “information” or “facts”, which tell us “how things are”, rather than as raw material for conjecture about “how things might be”. (p. 132)

In my experience, only a minority of students (even at 16 or 18 years of age) appreciate that theories are, in general, empirically under-determined. Nor do students always appreciate that creativity and imagination play a key role in their construction. Rather, many see theories as emerging relatively easily and painlessly from observations of phenomena and events or via experiment. When there is controversy, as in the case of evolutionary theory, for example, students may take the position that some theories are proven (by observation and experiment) while others are “just theories” – i.e., little more than “an idea” or speculation about how things might be explained.

Using interview methods and writing tasks, Joan Solomon and her colleagues have researched students’ understanding of the nature of theory and its relationship to experiments. Ideas about theories appear to fall into three major categories: (a) theory as a hunch or guess about what will happen, (b) theory as an explanation for why things happen (very close to the view we might wish students to hold), (c) theory as a set of facts. In these studies, students sometimes used the expression “proper theories” for those explanations that have been shown by tests and experiments to be “true” (Duveen et al., 1993; Solomon et al., 1994a, 1996). As I report in Hodson (2008), some students in my Toronto-based study took the view that theories are just guesses or speculations. Comments such as “that’s just a theory . . . it isn’t true” and “It’s just something that you think” were widespread, in some sense reflecting the everyday saying: “it may be OK in theory but it doesn’t work in practice”. Intriguingly, some students in the Solomon et al. (1994) study seemed to see experiment as a “last resort” when no-one knows what to do next, as revealed in comments such as “We’ll just have to do an experiment”. Among older students in my Toronto-based study there was sometimes a distinction drawn between “science as it ought to be” (the kind of science that is described in textbooks) and “science as it is” (what goes on in research labs), as in the study by Rowell and Cawthron (1982) noted earlier. Students were not expressing the view that scientists behave differently when self-interest, commercial interests or military interests intervene (although this awareness may be an important aspect of critical scientific literacy); rather, they were suggesting that the ideals of scientific inquiry are so demanding that they are beyond the reach of most ordinary students. Interviews with students undertaking research
projects as part of their final year programme at the University of Leeds revealed that undergraduates resemble secondary school students in regarding scientific knowledge as “provable beyond doubt” on the basis of experimentally acquired data (Ryder et al., 1999). In most cases, scientific inquiry was seen in terms of individual scientists seeking reliable data on which to base their conclusions, usually via experiment. Encouragingly, their appreciation of the role of theory in directing the nature of scientific inquiry became markedly more sophisticated during the course of the project work, though they remained relatively unaware of the internal and external social dimensions of scientific practice.

On a related theme, it is common for students to hold the view that when theories have gained substantial observational confirmation they become laws (Ryan & Aikenhead, 1992; Meyling, 1997; Brickhouse et al., 2002; Sandoval & Morrison, 2003; Dagher et al., 2004). The distinction between theories and laws is a recurring theme in the research conducted by Norman Lederman and his colleagues. The “approved position” is that laws describe relations and regularities among entities that can be readily confirmed by observations, while theories are complex explanatory systems (including the capacity to explain why particular laws hold) that are not susceptible to simple observational test and are, generally, empirically under-determined. While philosophers of science and some educational researchers may choose to draw such a distinction, most scientists do not. Most students also fail to recognize this distinction, and many refer to a hierarchical relationship in which theories become laws when there is sufficient supporting evidence. Moreover, many secondary school students know full well that Newton’s laws of motion are not laws at all, in the sense that they do not adequately describe the motion of objects travelling at close to the speed of light. They know, also, that the so-called gas laws do not describe the behaviour of real gases, though they do describe the behaviour of “ideal gases”. Several of the scientists interviewed by Wong and Hodson (2009) said that “law” is a confusing, unhelpful and outmoded term; it indicates a status that is inconsistent with the basic premiss that all scientific knowledge is subject to modification when there is appropriate evidence and convincing argument for change. In my view this is a timely reminder that in our search for an authentic view of science we should take note of what scientists tell us about their day-to-day practices. After all, does authentic science not mean the activities of real scientists rather than some philosophy-inspired idealization of practice?

IMPACT ON LEARNING

It is reasonable to speculate that students’ epistemological beliefs will impact their view of learning and their approach to problem-solving. Put simply, if students believe that scientific knowledge arises directly and unproblematically from observation they are likely to approach science learning in terms of memorizing facts, and they may expect to be able to prove that a hypotheses is correct (or false) by means of the scientific method. If they think of science as a continuing
process of concept development and theory building they will be more inclined to focus on conceptual understanding. That is, students’ epistemological beliefs may shape their metalearning assumptions and thus influence their learning orientations with respect to adoption of a performance orientation or a learning orientation (Kruglanski, 1989; Lidar et al., 2006).

In Tsai’s (1998) study, a Chinese version of Pomeroy’s (1993) questionnaire was used to ascertain the epistemological beliefs of approximately 200 high ability grade 8 students in a high school near Taipei City. Follow-up interviews identified 20 students with clearly articulated and strongly held views for subsequent interview concerning their learning orientations. Students who regard scientific knowledge as constructed through the creative efforts of scientists tended to employ more active and more constructivist learning methods; those students who believe that scientific knowledge arises from careful and systematic observation tended to use more rote learning strategies (see also, Halloun & Hestenes, 1998; Windschitl & Andre, 1998; Cavallo et al., 2003). The former group recognized the value of science in everyday life and were motivated to learn science largely by personal interest and curiosity; the latter group were motivated mainly by performance in examinations. Tsai reports that when students were asked to describe an ideal environment for learning science, the constructivist-oriented students emphasized opportunities to discuss with others, solve real life problems and control their own learning: the empiricist group said that they learn best, and minimize the anxiety associated with making mistakes, when teachers present scientific ideas clearly, facilitate the assembly of a good set of notes and help them to build up reliable store of “correct facts”. In a follow-up study with 1176 grade 10 students, those with a constructivist orientation were very critical of conservative teaching methods currently being used in their schools; they expressed a strong preference for approaches that would enable them to interact, negotiate meaning and build consensus with others, have enough time to integrate their new knowledge with their prior knowledge and experiences, exercise more control over their learning activities, and think independently (Tsai, 2000). Importantly, in the context of this book, constructivist students said that they try to use science in real life situations, while empiricists stated that science is not related to real life and has no value or application outside the classroom (see also Songer & Linn, 1991). Further, empiricist students seemed to lack a metacognitive perspective when learning science, and so focused on learning outcomes rather than learning procedures, while constructivist students tended to prefer learning in depth rather than breadth. This is significant, given that Hazari (2006) shows how a deep and narrow science curriculum in school (rather than broad and shallow) is strongly correlated with high levels of attainment in physics at university level, especially for female students.

Lin et al. (2004) show that students are likely to perform better on concept-based problem-solving (as distinct from algorithm-based problems) when they believe that observations are theory-laden, theories are constructed, and there is no single scientific method (scientists use whatever method is appropriate to the circumstances). Students who hold more traditional views, especially that there is
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one fixed, all-purpose method of scientific inquiry, perform less well on concept-based problems. However, their tendency to memorize information enables them to perform much better on assessment exercises that do not require knowledge integration and application. From lengthy interviews with 25 undergraduates studying chemistry, Havdala and Ashkenazi (2007) identified three individuals with clearly articulated but significantly different views about science, which the researchers designated as empiricist-oriented (observational data has priority over theory, which is seen as subjective), rationalist-oriented (theories are a sound guide to the validity and reliability of observations) and constructivist-oriented (both theory and observations are subjective and tentative). Subsequent observation of their responses to various laboratory-based activities revealed some fairly predictable differences in the way they prepared for the lab session, their approach to writing the lab report, the relative priorities afforded to theory and observation, and their ability to coordinate theory and empirical evidence. It was shown that over-confidence in one type of knowledge (theory or empirical knowledge) led to over-simplification of the relationship between theory and evidence.

SCIENCE AS A SOCIAL ENTERPRISE

Moss et al. (2001) state that, in general, grade 11 and 12 students’ understanding of the nature of scientific knowledge (for example, that it requires evidence, and is tentative and developmental) is more complete than their understanding of the scientific enterprise. If the term “scientific enterprise” is taken to include internal and external social factors that impact on the conduct of science, and is not restricted to the specific methods employed in particular scientific inquiries (or to what some teachers continue to refer to as “the scientific method”), then I would readily concur. Despite the efforts of the STS movement, many students continue to believe that science occurs in something of a sociocultural vacuum – a view held by both preservice and inservice science teachers in Tairab’s (2001) study.

Although some of the students in the study by Solomon et al. (1994) appreciated the importance of both collaboration and competition in stimulating scientific development, students generally have only a vague and fragmentary understanding of social factors internal to the practice of science. External influences are easier to recognize. Among the students with whom I have worked in Toronto schools, it is fairly common to hear the view that research funding should only be provided when scientists can demonstrate that their research will improve the quality of our lives in some tangible way. Science should, students often say, serve the public good. And many believe that it probably does. Although most students recognize how science (and, more particularly, technology) impact on society and the environment, with many being able to provide appropriate examples, they often have only a rudimentary understanding – beyond the issue of funding – of the ways in which sociocultural circumstances determine the kind of science that we do and may even impact the ways in which it is done. Interestingly, I have found greater awareness of these influences among students in New Zealand,
possibly as a consequence of repeated emphasis on Maori perspectives in the New Zealand curriculum (both in science and in other subjects). Nevertheless, Hipkins et al. (2005), writing from a New Zealand location though not necessarily from a New Zealand perspective, surmise that STS has served as a distraction from epistemological issues because once teachers have addressed the social and environmental impact of technology (simplistically regarded as applied science), many feel that they have “done” the learning about science component of the curriculum, and contentedly return to content-oriented teaching.

These observations serve to raise important questions about the extent to which social and cultural identity impact on a student’s NOS views. Cobern (1993, 1995, 1996) describes how different sociocultural environments produce different worldviews – defined as composite sets of consciously held and unconsciously held beliefs and values about the nature of reality and the generation of knowledge about it. These worldviews predispose an individual’s thoughts and emotions, and their everyday behaviours and actions, in particular ways. It would be surprising, then, if they did not impact on students’ views about science. Thus, we might anticipate some major cross-cultural differences in NOS understanding. Even within a particular society, the specific knowledge, beliefs, language, behaviours, values and aspirations acquired through membership of family and friendship groups may predispose students to particular views about science and scientists. So, too, might access to TV documentaries about science, visits to museums, zoos and science centres, all of which are contingent on students’ sociocultural location and socioeconomic status. For some students, religion may be one of those socioculturally located factors that impact quite substantially on NOS views, especially in the context of evolutionary theory or the moral-ethical issues surrounding genetic engineering and stem cell research (Dagher & BouJaoude, 1997, 2005; Roth & Alexander, 1997; Rudolph & Stewart, 1998; Ayala, 2000; Sinatra et al., 2003; Abd-El-Khalick & Akerson, 2004). Indeed, in some circumstances and with some individuals, it may well act as a boundary condition for entertaining scientific explanations at all; in effect, acting as a kind of roadblock that prevents students from recognizing and attending critically to data and ideas that are seen as constituting a challenge to religious convictions (Samarapungavan, 1997). Bybee (2001), Griffith and Brem (2004), Anderson (2007), Hermann (2008) and Martin-Hanson (2008) discuss pedagogical approaches suitable for teaching evolution as a controversial topic to students with strong religious beliefs, largely from a US perspective.

To investigate these influences, Dagher and BouJaoude (2005) used open-ended interviews to ascertain the perceptions of the nature of evolutionary theory held by 15 students majoring in biology at a private university in Beirut. Nine of the 15 students focused on the nature of the evidence and concluded that evolutionary theory is “deficient in meeting a criterion of ‘proof’ or evidence that is trustworthy” (p. 383). The authors state that although students may have only a fragmented and largely implicit view of what constitutes a scientific theory, they readily articulate some characteristics they claim to be “essential” or “crucial” when presented with a claim that they wish to reject because it clashes
with strongly held religious beliefs, worldviews, moral-ethical values or social expectations. Thus, evolutionary theory was considered to be deficient as a scientific theory because there is no direct observational evidence, it is not subject to experimentation, it was not derived in accordance with the steps of the scientific method, and is unable to make testable predictions – a set of specifications that the theory of plate tectonics, for example, is not required to meet. It seems that when students feel that religious or cultural beliefs and/or moral-ethical values are threatened they readily cite grounds for rejection of a theory that are accepted as perfectly legitimate in other circumstances. Sinatra et al. (2003) show that students who see knowledge as tentative and subject to change, and have a disposition towards open-mindedness, can come to an understanding of scientific explanations of controversial topics such as human evolution or the chemical origin of life, even if they do not necessarily accept them as “true explanations”. In other words, although they do not believe it, they understand why it is worthy of belief.

Problems resulting from a clash of worldviews have also been noted by Ogawa (1995) and Kawasaki (1996) with respect to some Japanese students and by Jegede (1998) with respect to African students. Aikenhead (1997) has reported at length on similar kinds of issues arising with First Nations students in Canada. For example, he argues that the interests of First Nations people in survival, coexistence and celebration of mystery are not in sympathy with the drive of Western science to achieve mastery of nature through objective knowledge based on mechanistic explanations. Nor are the holistic perspectives of Aboriginal knowledge, with its “gentle, accommodating, intuitive, and spiritual wisdom”, in sympathy with reductionist Western science and its “aggressive, manipulative, mechanistic, and analytical explanations” (p. 220). Crossing the border into the community of science education is inhibited not only by cognitive barriers but also by some of the distinctive values-laden features of science, features that are often distorted by school science curricula into the scientific cocktail of naïve realism, blissful empiricism, credulous experimentation, excessive rationalism and blind idealism noted by Nadeau and Désautels (1984). Sutherland (2005) notes that among the Cree students she interviewed, those who were able to distinguish clearly between Indigenous knowledge and Western scientific knowledge, and who could articulate different criteria of validity and applicability, were usually the most successful in learning science in school. Interestingly, Aikenhead and Otsuji (2000) report that Japanese teachers tend to view science from an holistic perspective, while Canadian teachers generally adopt an analytical and reductionist view. However, both groups of teachers seemed unaware of the ways in which science reflects and projects a particular set of socioculturally located beliefs and values that can constitute formidable barriers for some students. This research and theorizing tells us very clearly that careful consideration of issues in the history, philosophy and sociology of science are key to ensuring access to science for all students, and should be paramount in all efforts to re-build the curriculum.

Surprisingly, the Draw-a-Scientist Test tends to produce fairly consistent findings across cultures (Chambers, 1983; She, 1995, 1998; Parsons, 1997; Finson,
2002; Fong, 2002), although Song and Kim (1999) suggest that Korean students produce “slightly less stereotypical” drawings, especially with respect to gender and age. Generally, they draw younger scientists than their Western student counterparts – drawings that probably reflect the reality of the Korean scientific community. Using DAST and follow-up semi-structured interviews, Parsons (1997) elicited the images of scientists held by an all-female group of 20 high ability African American students. Eleven respondents drew and described their scientist as a White male, four as a Black male, two as a Black female and one as a White female. The most striking difference in the descriptions was that between the White male scientist and the Black male scientist. Both were perceived as intelligent and hard-working, but whereas White scientists were described as exhibiting the usual negatively stereotyped characteristics (being aloof, odd, and probably friendless), Black male scientists were portrayed as kind, respectful, easygoing and responsive to the needs of others. The author concludes that this picture of the Black scientist is consistent with what she refers to as “the Black Cultural Ethos” – the way African American people are expected to be, by other members of the community. In a study of 358 students in grades 1–7 in South West Louisiana, Sumrall (1995) found that African Americans (especially girls) produced less stereotyped drawings than Euro Americans with respect to both gender and race. Interestingly, the drawings of African American boys showed an equal division by race of scientist but an 84% bias in favour of male scientists. Indeed, many researchers have pointed out that girls are generally less stereotyped in their views about science and scientists than are boys, except in relation to social aspects (see earlier discussion). However, Tsai and Liu (2005) note that female Taiwanese students are less receptive than male students to the idea that scientific knowledge is created and tentative, rather than discovered and certain.

In a study of the images of science and scientists held by preservice teachers in Israel, Rubin et al. (2003) found that the drawings of Hebrew-speaking students conformed to the usual stereotypes of bald men in lab coats and wearing glasses, but the drawings of Arabic-speaking students showed men with beards and moustaches wearing traditional tunics (not lab coats). When asked to name five scientists, the Hebrew speakers tended to nominate Einstein, Newton, Galileo, Darwin and Pasteur, while the Arabic speakers often included Ibn Sina, al-Razi, al-Ghazali and al-Khawarizmi. Interestingly, when I tried a similar exercise with 27 serving teachers enrolled on an MEd programme at the University of Hong Kong, there was not a single Chinese scientist in anyone’s list, though my Canadian students always include the name of Frederick Banting. If Tao (2003) is correct in reporting that Hong Kong students generally hold very traditional stereotyped views on NOS issues, my finding should not have been surprising, even though it was disappointing. Of course, it should also be noted that stereotyped views about science do not prevent Hong Kong students performing exceptionally well in international tests of science attainment.

Liu and Lederman (2002) report that Taiwanese students display more sophisticated understanding of NOS issues (as measured by a variant of the VNOS questionnaire) than is usual among American students. Although it should be
noted that the Taiwanese population tested were designated as “gifted students”, the authors report that an earlier study (by Lin) of 1670 senior high school students with a “more normal distribution of abilities” gave similar results. In contrast, Kang et al. (2005) suggest that Korean students (at grades 6, 8 and 10) are much more likely than Western students to hold the naïve view that scientific knowledge is true (in an absolute sense) because if this were not the case, “we wouldn’t have to learn it in school”. Theories change because “the old ones were proved to be wrong” by means of experiments, largely as a result of using better equipment or new technologies. Following a questionnaire-based study with more than 2000 grade 10 students in Turkish high schools, using a shortened and modified form of VOSTS, Dogan and Abd-El-Khalick (2008) conclude that the majority of students, and their teachers, hold naïve views on many aspects of NOS. More encouragingly, students and teachers hold “meritorious” or “informed” views with respect to the theory-driven nature of scientific observation (64.6% and 53.5%, respectively) and the tentativeness of scientific knowledge (68.2% and 72.7%, respectively). The researchers note that students living in regions that are “more European-like in culture (i.e., Marmara and Aegean)”, tend to have more informed NOS views than those living in areas that are “more Eastern-like in their cultural overtones (i.e., Southeast and East Anatolia)” (p. 1102). Griffiths and Barman (1995) interviewed 96 students, drawn equally from high schools in Canada (mean age = 17.6 years), the United States (mean age = 16.9) and Australia (mean age = 16.5), about NOS issues – particularly, the nature of scientific inquiry, the role of observation, the tentative nature of scientific knowledge, and the status of scientific theories. While the very small samples preclude any firm international comparisons, there are some interesting and noteworthy differences. The lock-step view of scientific method was cited by 75% of US students but not at all by Australians; 40% of Canadian students, but only 15% of Australians and 0% of Americans, said that science changes over time because of the influence of new ideas; the theory dependence of observation was acknowledged by many more Canadian students than by Australian or US students. Of particular relevance to notions of critical scientific literacy, with its emphasis on politicization of students and promotion of responsible citizenship, is Liu and Lederman’s (2007) Taiwan-based exploration of the interactive relationship between an individual’s worldview and their conceptions of the nature of science. Most notably, student teachers with “informed” NOS views (as measured by a variant of VNOS) tend towards a biocentric view of the environment, while those with “naïve” views were more inclined to an anthropocentric view.

All of these findings point to one simple conclusion: if we change the curriculum we can be sure that student understanding will change, though we may not be able to predict in exactly what ways or to what extent. Also, given the ubiquity of the Internet and other contemporary ICT media, we can no longer rely on the old adage that “students won’t learn what they are not taught”. In the contemporary world, people may learn as much (if not more) about science from these sources as they do from the formal science curriculum. This realization makes it imperative that science teachers address NOS issues carefully, systematically and rigorously,
and seek to subject the ideas students acquire from informal sources to rigorous critical scrutiny. Of course, as the research makes clear (if we need research to point out such an obvious conclusion), different curriculum experiences and out-of-school experiences result in students holding different views about science and scientists. As Driver et al. (1996) comment, the tendency of many students in the United Kingdom to regard experiments as a comparison of outcomes of different initial conditions is undoubtedly a consequence of the emphasis on “fair tests” in the National Curriculum for England and Wales. Also, the weakness of many students in model-based reasoning may be a direct consequence of the lack of emphasis on these matters in the classroom and textbooks, rather than a generalized inability to reason this way (see discussion in Chapter 6). As always, research has to be interpreted with great caution. Questions that spring to mind concern: (i) the potential for changing students’ views through judicious curriculum interventions, and (ii) the extent to which students’ views are a consequence of teachers’ views transmitted implicitly or explicitly through the curriculum. It is this second matter that I address in Chapter 3.

NOTES

1 This instrument has subsequently been modified to produce the Views of Nature of Science questionnaire (Lederman et al., 2002), and further modified by Lederman and his co-workers (Lederman, 2007) and by Wong and Hodson (2009).

2 Finson et al. (1995) have developed a checklist for identifying and quantifying the components of students’ drawings for more efficient data analysis.

3 614 students used data-focused reasoning on at least one occasion; 303 used radical relativist reasoning on at least one occasion; 728 used theory and data related reasoning on at least one occasion; 609 used both data focused and theory and data related reasoning; 239 used all three forms of reasoning.

4 Repertory grids enable researchers to ascertain links between different facets of an individual’s knowledge and understanding (and between understanding and actions) in quantitative form (Fransella & Bannister, 1977). Using them over the lifetime of a research project enables a developmental record of students’ (or teachers’) views to be built up. Because repertory grids often produce surprising data and highlight inconsistencies in respondents’ views, they provide a fruitful avenue for discussion and exploration of ideas. For these reasons, Pope and Denicolo (1993) urge researchers to use them as “a procedure that facilitates a conversation” (p. 530).

5 Given the situation 20 years on, and the suspicion with which scientific claims are sometimes greeted, one wonders whether similar results would be obtained today with respect to trustworthiness.

6 Chambers (1983) notes that some students’ drawings of scientists included notices on doors or cabinets that said “Private”, “Top Secret” and “Keep Out”.

7 This perfectly describes my own experience as a researcher in synthetic organic chemistry some 40+ years ago.

8 Chapter 4 includes some discussion of how explicit and reflective instruction in modelling can assist students in progressing through this hierarchy.

9 Some teachers choose to avoid this problematic situation, especially with experiments that are central to building particular conceptual understanding, by engaging in what Nott and Smith (1995) and Nott and Wellington (1996) refer to as conjuring – that is, ensuring “correct results” by sleight of hand or manipulation of apparatus and materials.

10 In a subsequent publication, Tsai (2003) reports that having a constructivist orientation increases the likelihood of students negotiating the meaning and significance of experiments with their peers.
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11 Frederick Banting, a Canadian, shared the 1923 Nobel prize for medicine with John MacLeod for their discovery of insulin.

12 They also held a strongly stereotypic image that science is a product of Western society. Few students could name a Chinese scientist.