

From the Horse's Mouth: What Scientists Say About Scientific Investigation and Scientific Knowledge

SIU LING WONG, DEREK HODSON

*Faculty of Education, The University of Hong Kong, Hong Kong SAR,
People's Republic of China*

*Received 16 October 2007; revised 7 February 2008, 17 April 2008;
accepted 22 April 2008*

DOI 10.1002/sce.20290

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: This study sought to identify prominent features of the nature of science (NOS) embedded in authentic scientific inquiry. Thirteen well-established scientists from different parts of the world, working in experimental or theoretical research, in both traditional fields such as astrophysics and rapidly growing research fields such as molecular biology, completed an open-ended questionnaire about the NOS and participated in in-depth interviews. The descriptions of their practices provide a somewhat striking contrast to the image of science usually portrayed in science curricula and textbooks. These accounts of authentic scientific practice have considerable potential for development into interesting cases as teaching resources to enhance and enrich students' understanding of NOS and for the design of more effective laboratory work and field experience. © 2008 Wiley Periodicals, Inc. *Sci Ed* 1–22, 2008

INTRODUCTION

Understanding the nature of science (NOS) has long been regarded as a major component of scientific literacy and an important learning objective of science curricula (e.g., American Association for the Advancement of Science, 1993; Council of Ministers of Education,

Correspondence to: Siu Ling Wong; e-mail: aslwong@hkucc.hku.hk

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Canada, 1997; Millar & Osborne, 1998; National Research Council, 1996; United Nations Educational, Scientific and Cultural Organization, 1993).¹ In making the case for NOS knowledge in the curriculum, Driver, Leach, Miller, and Scott (1996) contend that in addition to its intrinsic value, it 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. However, while there has been extensive research on students' and teachers' conceptions of NOS and numerous efforts to develop more effective NOS-oriented curricula, robust understanding of NOS for all is still far from being achieved. Indeed, it has been consistently reported that both students and teachers possess inadequate, incomplete, or confused NOS understanding (Abd-El-Khalick & Lederman, 2000; Driver et al., 1996; Finson, 2002; Hogan & Maglienti, 2001; Lederman, 1992; Moss, Abrams, & Robb, 2001; Ryder, Leach, & Driver, 1999). Regrettably, the goal of improving NOS understanding is often prejudiced by stereotyped images of science and scientists consciously or unconsciously built into school science curricula (Hodson, 1998) and perpetuated by science textbooks (McComas, 1998).

Running alongside and complementary to these arguments for NOS is the case for a more authentic science education—that is, an approach to learning science that has much 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)

To meet the first two curricular characteristics, it is necessary to know (i) what constitutes an authentic view of scientific practice, and (ii) how that understanding can be conveyed to students in an effective and an efficient way.

IN SEARCH OF AN AUTHENTIC VIEW OF SCIENCE

It is now more than 20 years since Laudan et al. (1986) stated:

We have no well-confirmed general picture of how science works, no theory of science worthy of general assent. . . . If any extant position does provide a viable understanding of how science operates, we are far from being able to identify which it is." (p. 142)

More recently, a questionnaire-based survey of 210 philosophers of science generated data that led Alters (1997) to the same conclusion. Nevertheless, according to McComas and Olson (1998), there is substantial agreement within a number of recent science curriculum reform documents produced in the United States, United Kingdom, Canada, Australia, and New Zealand concerning the elements of NOS that should be included in

¹ 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). In common with definitions adopted by Osborne et al. (2003) and Clough (2006), the term NOS used in this paper 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.

the school science curriculum—a view endorsed by Abd-El-Khalick, Bell, and Lederman (1998), McComas, Clough, and Almazroa (1998), and Cobern and Loving (2001). Indeed, Abd-El-Khalick et al. (1998) and Lederman, Abd-El-Khalick, Bell, and Schwartz (2002) state that while philosophers and sociologists might disagree on some aspects of NOS, the nature and substance of these disagreements are generally irrelevant to K-12 students and their teachers.

In an effort to illuminate these matters further, Osborne, Collins, Ratcliffe, Millar, and Duschl (2003) conducted a Delphi study to determine empirically the extent of agreement among 23 participants drawn from the “expert community” on what ideas about science should be taught in school science. The participants included five scientists, five persons categorized as historians, philosophers and/or sociologists of science, five science educators, four science teachers, and four science communicators. Although there were differing views among individuals, there was broad agreement on nine major themes: scientific method and critical testing, creativity, historical development of scientific knowledge, science and questioning, diversity of scientific thinking, analysis and interpretation of data, science and certainty, hypothesis and prediction, and cooperation and collaboration. A comparison of these themes with those arising from the analysis of science education standards documents by McComas and Olson (1998) reveals many similarities. Essentially, the same list is found in Lederman et al. (2002): science is tentative, empirically based, subjective (in the sense of being theory driven), socioculturally embedded, and dependent on human imagination and creativity. These authors are also concerned that students appreciate that there is no one scientific method, draw a distinction between observation and inference, and recognize the difference between theories and laws.²

Although their research establishes clear support for including this particular list of NOS items in the science curriculum, Osborne et al. (2003) express concern that the items might be regarded by teachers as *discrete* components and might be taught in an abstract, decontextualized way. Elby and Hammer (2001) had previously argued that the current consensual list of NOS items is too general and too broad, and that it is neither valid nor productive of good learning about science. We concur with their claim that “a sophisticated epistemology does not consist of blanket generalizations that apply to all knowledge in all disciplines and contexts; it incorporates contextual dependencies and judgments” (p. 565) and with Rudolph’s (2000) argument that teachers should acknowledge the context dependency of scientific practice and knowledge generation:

Educators need to begin to exploit the vast literature of the science studies community, not to develop some universalist picture of science, the value of which is questionable, but to begin to understand what the various practices of science look like in all their myriad forms, in order to provide some reasonably authentic context in which to situate the scientific knowledge claims of the curriculum. (p. 409)

It is interesting that Rudolph puts his faith in the sociologists and ethnographers who contribute to the science studies literature to provide an *authentic* view of science and scientific practice—a view endorsed by McGinn and Roth (1999) and recent work by Ford and Wargo (2007). While we acknowledge that the work of Bruno Latour, Steve Woolgar, Steve Fuller, Harry Collins, Karen Knorr-Cetina, and others, has added much to our understanding of both the internal and the external social influences on scientific practice, we urge that these pronouncements on scientific practice be tempered by *reflective*

² Lederman et al. (2002) state: “laws are descriptive statements of relationships among observable phenomena. . . Theories, by contrast, are inferred explanations for observable phenomena or regularities in those phenomena” (p. 500).

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critical comments from practicing scientists. After all, as Wolpert (1994) and Labinger (1995) remind us, scientists frequently do not recognize themselves or their actions in some of the ethnographic studies that have been published in recent years. Recognizing that events can be interpreted in diverse ways, according to the particular theoretical frameworks adopted, is an important element of the critical scientific literacy that science teachers seek to cultivate in their students. The same considerations should pertain to issues of curriculum design: We should balance the conclusions of the science studies literature with comments gathered from those who conduct the day-to-day business of science (i.e., practicing scientists).

Some years ago, Fensham (2002) argued that “it is time to change drivers for scientific literacy” because, for years, our ideas about the essential elements of scientific literacy have been determined by science educators, with little attention being paid to the views of those working in science-related professions and industries. Similarly, the elements of NOS included in science curriculum standards documents are mainly developed by science educators, albeit from extensive study of the literature produced by philosophers, historians, and sociologists of science. We believe that scientists who work at the frontiers of science can play an important role in refining and developing science educators’ views about the practices of the science community, the nature of scientific work, the aims behind it, and the interrelationships with the society in which it is embedded. The study described here is a response to recent advocacy of a move from the global to the local, from epistemological abstractions that exist only in school textbooks and national policy documents to epistemological frameworks, and norms defined and exemplified by real-world communities of practitioners (Elby & Hammer, 2001; Rudolph, 2000, 2003). The perspectives on NOS provided by active practitioners in the science community primarily concern day-to-day practices rather than wider epistemological issues, and are intended to illuminate, enhance, enrich, and qualify the views provided by experts in other communities.

Although two early studies (Kimball, 1968; Pomeroy, 1993) compared views of NOS between scientists and science teachers, both authors noted that their research had limited generalizability because of geographically narrow sample populations. The scientists in Kimball’s study were all graduates from two universities in California, whereas Pomeroy studied a group of scientists located exclusively in Alaska. Most of the scientists in Kimball’s study had relatively short research experience, with a maximum of 6 years. Furthermore, the two studies used standardized forced-choice and Likert-type paper and pencil assessment instruments, which have often been criticized on the grounds of vulnerability to inconsistencies of interpretation of the survey statements between researchers and respondents. While we acknowledge the inclusion of five scientists in the Delphi study conducted by Osborne et al. (2003), it is possible (even likely) that the contextual dependency of scientific inquiry may have been lost in the process of compiling a consensual list of NOS themes. Previously, Glasson and Bentley (2000) had interviewed four scientists and two engineers following a conference in which they had presented their work to K-12 educators. The authors report that the scientists and engineers described a wide range of scientific methods but did not explicitly discuss their views of NOS during their presentation; however, in the interviews they expressed a commitment to empiricism and emphasized science, technology, and society connections to their research. The authors suggest that more dialogue between the scientific community and science educators about NOS, science–technology–society, and related curriculum issues might further enhance understanding of these issues—a view that we share.

We are encouraged to see increasing numbers of science educators paying attention to the voices of scientists. For example, Samarapungavan, Westby, and Bodner (2006) have

compared the NOS beliefs of 13 research chemists with those of chemistry students ranging from high school to postgraduate level. Their results suggest that the current characterization of NOS in science education may underrepresent discipline-specific aspects of science. Schwartz and Lederman (2006) explored the contextually based views of NOS and scientific inquiry possessed by 24 scientists from different disciplines, including chemists, life scientists, and physicists. They reported that, in general, epistemological views do not seem to differ across disciplines, although some subtle differences are apparent in relation to the specific research contexts of individual scientists.

We see another need to elicit scientists' views of NOS: rapid advances in scientific knowledge and investigative procedures over the past few years, particularly in the biological sciences. Like Lederman (1992), Losee (1993), and Heidelberger and Stadler (2002), we believe that NOS understanding is as tentative and subject to change as scientific knowledge itself, and we question whether the consensual list of NOS elements any longer fully reflects 21st-century scientific practice. Indeed, we contend that much of what we currently present to students through the science curriculum is confused, confusing, and out of date. The inclusion of scientists in the newer scientific domains in our study is specifically intended to address this concern and provide insight into aspects of NOS in contemporary science that should be afforded greater attention.

PROVIDING AUTHENTIC EXPERIENCES

A number of science educators argue that a clear understanding of what constitutes authentic scientific practice can best be acquired, and perhaps can only be acquired, by first-hand apprenticeship experience in a laboratory or field setting (Helms, 1998; Roth, 1995). Not only are these internship experiences difficult to provide for every student, especially in Asian countries such as China, Japan, and Korea, where class sizes are commonly as high as 50 students, they do not always bring about the desired understanding as quickly and straightforwardly as intended. As Bell, Blair, Crawford, and Lederman (2003) and Schwartz, Lederman, and Crawford (2004) report, it seems that it is not the doing science activity per se that is key, but reflection on these experiences through journal writing and seminars. However, it may be possible to present something approximating to authentic scientific investigation during regular laboratory and fieldwork activities, provided that due cognizance is taken of the potential conflicts between activities designed to bring about particular conceptual understanding and activities intended to give students experience of doing science (Chinn & Malhotra, 2002; Hodson, 1994, 1998). Buxton (2006) provides an insightful discussion of many additional problems associated with the design and implementation of experiences focused on aspects of authenticity. Extended project work, in which students identify the area of concern, formulate the research questions, design the investigation, collect, interpret and report the data, and argue for particular conclusions, is authentic science from the perspective of the student. Such experiences can be enormously enhanced by providing opportunities for students to consult practicing scientists via contacts with a local university or college (Bencze & Hodson, 1999), through involvement at a community science center or science camp (MacDonald & Sherman, 2007; Richmond & Kurth, 1999), or through telemonitoring and related ICT technologies (Comeaux & Huber, 2001; Lee & Songer, 2003; O'Neill, 2001).

There is also some encouraging evidence that well-designed historical case studies can be effective in bringing about NOS understanding. For example, Irwin (2000) reports encouraging results with a group of 14-year-old students when substantial amounts of historical material were integrated into the topic of *Atoms and the Periodic Table*, whereas Lin and Chen (2002) provide evidence of positive impact on understanding of NOS among a

group of prospective chemistry teachers by integrating historical cases into their preservice teacher education program. It is our contention that case studies of *contemporary* practice, or “science-in-the-making” as Latour (1987) calls it, would be even more effective. Situating the NOS elements in contexts of authentic science practice may help to dispel some persistent stereotypes about science, resolve some seemingly contradictory NOS elements found in curriculum documents, and illuminate the changing nature of NOS. This was the stimulus for approaching a number of leading scientists with an invitation to talk about their day-to-day research activities. Put simply, the goal was to collect data to enable us to present students and teachers with a more authentic view of scientific practice in the early 21st century. The advantage of presenting cases of contemporary science is the ease of direct communication with scientists who live at the same time and in the same place as the students. The feeling of closeness and the opportunities for learners to ask for details of science practice directly from the scientists may provide an effective basis for them to learn about science more enthusiastically.

In this paper, we report on some interesting commentaries on scientific practice provided by the scientists to illustrate various NOS elements, *both within and outside* the consensual list. These examples are compared and contrasted with the image of science and science practices portrayed in contemporary science textbooks and curriculum documents. We also discuss the potential of the accounts of authentic practice for designing more authentic laboratory activities and constructing case studies of contemporary scientific practice.

INTERVIEW WITH SCIENTISTS

Convenient and purposive sampling was adopted in this study. The first author, who was formerly an active scientist with direct and indirect connection with many well-established scientists in various fields, invited appropriate subjects to take part in our study. Our first selection criterion was set in response to the call from Rudolph (2000, 2003) to probe the diverse practices existing within and across scientific disciplines. Hence scientists from a wide range of research fields were approached. By contacting scientists in a number of different countries, we also addressed the sample limitation highlighted by the researchers in two early studies (Kimball, 1968; Pomeroy, 1993). It should be noted that our research was not intended to produce a sample of scientists representative of all sociocultural locations and all disciplines. Rather, our purpose was to ascertain whether there are any commonalities and differences in views about NOS through their personal experience of doing science among a diverse group of practicing scientists. We were particularly interested in the extent to which those working at the “cutting edge” of science hold views that are similar or dissimilar to the views currently being promoted in the science education literature (see earlier discussion), and in what ways they might support or challenge the views commonly promoted via school science textbooks. At the heart of this latter concern was speculation that advances in knowledge and procedures in rapidly growing fields such as molecular biology, stem cell research, and materials science might already have rendered such views obsolete. We therefore included a number of scientists active in these research fields. Finally, invitations were issued on grounds of reputation for research productivity and eminence in the field.

Thirteen scientists accepted our invitation and expressed support for our project; two declined because of excessive work commitments. The lengths of the scientists’ research careers to date ranged from 10 to 32 years. The scientists are located in different parts of the world: the United States, United Kingdom, Switzerland, New Zealand, and People’s Republic of China. Ten of them have worked in more than one country, and collectively

TABLE 1
Details of the Participating Scientists

Scientists [Male (M)/Female (F)]	Major Areas of Research	Research Experience (Years; Places of Work)
High-energy physicist (M)	High-energy physics, cellular automata, and morphology-dependent resonances	17; UK, United States, China
Experimental particle physicist (M)	Elementary particle physics, radiation shielding calculation	14; UK, United States, Switzerland
Materials scientist (M)	Material characterization, spectroscopy, microscopy of nanostructures	19; UK
Theoretical astrophysicist (M)	Astrophysics, quantum mechanical computation, and nonlinear physics	16; United States, China
Theoretical solid-state physicist (M)	Electronic and optical properties of rare earth ions in crystals, application of group theory to spectroscopy	26; New Zealand, United States, China
Cancer biologist (F)	Cancer research and its applications	32; China
Medical geneticist (M)	DNA test on prenatal diagnosis, cancer detection and monitoring	20; UK, China
Virologist (M)	Molecular determinants of influenza genes, vaccine research	10; UK, China
Molecular biologist (M)	Molecular biology, genomics, bioinformatics	13; China
Stem cell biologist (M)	Stem cells and gene transfer	26; Australia, China
Cell biologist (M)	Cell cycle control, regulation of cell size	2;0 UK, China
Biochemist (M)	Construction and characterization of hybrid enzymes, protein engineering	15; UK, China
Director of research initiatives (formerly experimental semiconductor physicist) (M)	Creating research partnerships between government, industry, and the university	15; UK, United States

their experience spans a wide range of sociocultural settings. The selection criterion of research productivity and international eminence, together with the desire to ensure a wide disciplinary sample, resulted in 12 of the participating 13 scientists being male. Although a more equitable gender balance would have been desirable, we recognize that this imbalance reflects the reality of senior positions in many prestigious research establishments. Details are summarized in Table 1.

A modified version of the open-ended questionnaire, *Views of Nature of Science Questionnaire* (VNOS-C), developed by Lederman et al. (2002), was chosen as the primary data-gathering instrument. VNOS-C is an open-ended instrument, which in conjunction with individual interviews can provide meaningful assessments of respondents' NOS views.

Instead of trying to assess whether the scientists possess what some science educators have termed “adequate views” about science (with reference to the consensual list of NOS items), the modified questionnaire aimed to elicit as much detail as possible about scientists’ *actual* views on NOS and, more importantly, to act as a prompt for them to talk about the ways in which their views are exemplified in their current work practices. The original 10 questions of VNOS-C were slightly rephrased to achieve these purposes. In recognition that the 10 questions of VNOS-C only sought views on certain NOS aspects which focus mainly on nature of scientific knowledge, we included additional questions for soliciting scientists’ views on the characteristics of scientific inquiries and the social interaction within and beyond the scientific community. These questions led to scientists’ views on topics including the ways in which scientists design and conduct their inquiries; the social, political, and economic constraints faced by scientists; and the processes by which scientific knowledge is constructed and validated. We also asked about the desirability of including explicit teaching of NOS in the school science curriculum, particularly in view of the reduced time that would be available for covering subject content knowledge. The questionnaire was sent to the scientists immediately after their acceptance of our invitation to participate, some several weeks before the interview. This allowed them adequate time to relate their research experience and other relevant experience to their views on NOS, and created an opportunity for them to reflect upon their views on NOS. At the beginning of the interview, we reiterated that our principal goal was the NOS as reflected in their science practice. Participants were encouraged to share as much detail as possible of the features of scientific practice related to or beyond the areas covered in the questionnaire. Indeed, many scientists commented during interview that they had never seriously pondered these questions before participating in our study. In-depth interviews of 90–180 minutes duration were conducted to elaborate on scientists’ questionnaire responses and furnish detailed descriptions of individual views on science and day-to-day scientific practices. Face-to-face interviews were conducted with eight scientists; interviews with the remaining five were conducted by telephone. Some later clarification of data was carried out via e-mail correspondence and follow-up telephone calls. The face-to-face interviews were videotaped, and the phone interviews were audiotaped. The data were subsequently transcribed for analysis. The final transcriptions were sent to all participating scientists for confirmation of an accurate record of the interview. Of course, there is no guarantee that scientists are always truthful in their self-reports of daily practice, though we did ensure that all participants appreciated that our research purpose was focused very directly on actual scientific practice and how that might resemble or differ from textbook descriptions. Most of the scientists expressed strong support for this endeavor and were keen to assist us, so we have good grounds for believing that their descriptions were faithful to their actual practice.

DATA ANALYSIS

Regular meetings were held between the authors to identify, discuss, and reach agreement on the NOS aspects embedded in the responses to the questionnaire and in the interviews with scientists. The embedded NOS features were first identified with reference to the list of advocated NOS features found in curriculum standards documents. Additional NOS elements were established to cover prominent features identified in the scientists’ interviews which did not fall under the existing list of NOS elements generated from curriculum standards documents (McComas & Olson, 1998). Full agreement of authors on the finalized list was achieved concerning eight prominent categories: (1) methods of scientific investigation (including the role of hypothesis and the design of experiments); (2) the significance of theory in scientific inquiry (including thoughts on observation and inference); (3) the

tentative NOS (including warrant for belief and the status of laws and theories); (4) creativity in science (before, during and after data collection); (5) social, political, economic, and cultural influences on science; (6) research-funding issues, academic freedom, and ethics; (7) collaboration and competition; and (8) peer review. For the purposes of this paper, data in the first four of these categories have been collapsed into two major themes: (i) methods of scientific investigation and (ii) the role and status of scientific knowledge.

A subsequent article will report on science as a social practice (the third themes encompassing categories 5–8). These three themes were chosen because they constitute three major areas of misunderstanding for learners. It should be noted that substantial overlap of NOS features described under each theme, and linkages between the three themes, are apparent in the scientists' descriptions.

WHAT THE SCIENTISTS TOLD US ABOUT METHODS OF SCIENTIFIC INVESTIGATION

Variation of Scientific Investigation

Given the high status of “experiments” in the rhetoric of school science education, it would be quite startling for students to be confronted by an insistence on the demarcation between theoretical and experimental physics and by a statement from the high-energy physicist that he *never* does experiments.

I don't do experiments . . . The experiments of physics have become larger and larger in scale, especially in my specialty. Also, those related theories are becoming more complicated. . . It is difficult for scientists to deal with both theoretical and experimental issues at the same time . . . If you've ever read about history of physics then you've probably heard that Fermi, who died about 50 years ago, was the last one to be both a theorist and an experimentalist. (High-energy physicist)

He went on to state that the approach taken in an investigation can be very flexible and depends on the particular circumstances.

I do not have any specific stepwise procedure to do research . . . To solve problems, I will use whatever means I can get, including reading books and others' [scientists'] papers, asking and talking to people, developing some mathematical tools to see if they can be developed into certain theories which explain existing data . . . No rigid and systematic procedure.

In terms of method, the high-energy physicist told us that “there is no particular procedure . . . the process is quite chaotic, with ideas or problems ‘jumping’ here and there” but there are “some follow-ups which are more procedural.” The cancer biologist also stressed that “flexibility of approach” is the key to advances in science. However, it is evident that scientists often play different games on different occasions, as described by the biochemist.

When we have to exchange ideas with other research groups worldwide, we need to present our ideas in the form of a paper containing some standard elements such as title, abstract, introduction, scientific methods, results, conclusion and lots of references. This is the rule of the game and we have to follow it. It is necessary for us to present our results and let others understand. However, step-wise methods do not apply to the process of idea generation. (Biochemist)

In essence, our scientists were giving support to Medawar's (1963) assertion that the scientific paper is a fraud: a rational reconstruction of events as a means of arguing a case,

rather than a “blow-by-blow” account of the research. The rationality of the chosen method is only seen afterward, when satisfactory conclusions have emerged.

Unsurprisingly, a number of the scientists identified “making hypotheses” as a typical step in *most* of their research and stated that they often have expectations about the research results. In many ways, it is the hypothesis that guides the design of the investigation. However, the astrophysicist told us that although his own work is almost invariably hypothesis driven, this is not necessarily the case for other scientists. Astronomers, he said, “often look at the sky without purpose . . . they are just shooting in the dark (!),” and those working on the human genome project, for example, have only a very distant and all-encompassing hypothesis (that there is an ordered structure) to guide them. The cancer biologist confirmed that much of her research involves a stage of relatively unguided data collection: “working to obtain information to build up the whole picture,” with each member of the research team being assigned a different focus.

The molecular biologist said that in genomics research scientists have to *pretend* to be engaged in hypothesis-driven research because funding bodies regard purely open-ended work as little more than a “fishing expedition.” But without these fishing expeditions, he said, potentially crucial information will be missed. “We won’t know the significance of any one piece of data if we don’t have it all, which is why we need many groups of researchers, each working on a different aspect of the project.”

We want to find out all the human genes, but we don’t know the problem we are going to solve . . . I pick out a gene and try to characterize it. Before I start working on it I haven’t the slightest idea about it and I don’t know if it is related to the heart or the liver . . . It is impossible to have any hypothesis beforehand. However, this is problematic when applying for grants . . . it is regarded as a fishing game instead of a scientific process . . . But if we are not working in this way, but always based on a problem, some genes will never be characterized . . . It’s like playing a puzzle. If you don’t want to miss a piece, you have to explore . . . Sometimes it’s building up a platform for other researchers. (Molecular biologist)

He also commented that technology has had a major impact on the design of scientific research. Indeed, we were told several times that recent advances in technology have resulted in knowledge generation without the need to make hypotheses, especially in fields such as molecular biology and materials science.

In the past . . . science was almost always based on hypothesis, followed by some testing . . . Recent science is not always hypothesis-driven—for example, the multi-national project of sequencing of the human genome . . . It is generating very useful scientific knowledge without any prior hypothesizing. (Medical geneticist)

I sometimes try to minimize the amount of hypothesis or assumed knowledge. For example, I have recently embarked on a journey into hyperspectral imaging where I collect as much data as possible and then allow computers to extract as much information with as little prior “expert knowledge” as possible. (Materials scientist)

The materials scientist, medical geneticist, and virologist all commented that in “the old days” it took days or even weeks to plan and conduct an experiment because each data collection process was very time consuming. With recent advances in technology, most of the tedious data collection is now carried out by high-speed computers. Data collection that previously took months to complete now only takes minutes. The much reduced data generation time makes meticulous hypothesizing and theorizing before actual experimenting less important than in the past. Scientific investigations in which data are obtained first

and then interesting problems are identified by “data mining” have become much more common in recent years. This feature of contemporary practice runs counter to a common textbook assumption that science follows a rigid stepwise procedure, beginning with the formulation of a hypothesis. It also illustrates the dynamic interrelationship of science and technology. Naively, students often think that “science comes first and technology follows.” The following comment by the medical geneticist may help to dispel this myth:

The scientific knowledge about the DNA structure and the DNA sequencing reaction leads to the production of DNA sequencers . . . With the DNA sequencers, DNA sequence can be obtained in a much reduced time . . . leads to the cracking of the entire human genome.
(Medical geneticist)

In other words, advances in science bring about advances in technology (such as new scientific instruments) and, in turn, this new technology stimulates advances in science. Technology does not just extend our capacity to “see and hear,” it gives us new ways of seeing and hearing. The cancer biologist also argued that improvements in technology make science “more objective” by reducing our dependency on the (inevitably) subjective interpretation of data, though she was not tempted into commenting on the theoretical assumptions underpinning the design of scientific instruments and whether this posed a counterargument to her view on enhanced objectivity.

Creativity and Imagination Versus Objectivity

All scientists in our study stated that creativity and imagination are important *at all* stages of an investigation (planning and designing; data collection; data interpretation), though the nature and extent of creativity and imagination may vary between stages. In contrast to beliefs commonly promoted by school science textbooks, that creativity is unnecessary (or even inappropriate) during and after data collection and that careful, dispassionate, and systematic analysis of data will lead unerringly to secure conclusions, the materials scientist told us that:

The design of a good experiment must involve a great deal of creativity in overcoming limitations, problems, etc. Likewise for the collection of data . . . creativity and imagination can also be important for saving time and labour. The analysis of data can be enhanced by these skills but clearly within a tight framework that does not over-interpret or modify data.
(Materials scientist)

The astrophysicist also reminded us that creativity must be balanced with caution: “Assume with daring; verify with care . . . If you are always imaginative, you are just a day-dreamer.” In terms reminiscent of Mitroff and Mason’s (1974) distinction between *extreme speculative scientists* and *data-bound scientists*, the molecular biologist talked about the need for two kinds of scientists: those whose strengths lie in rigorously and logically applying what we regard as secure knowledge to generate accurate and reliable data, and those with “researcher wisdom,” who are flexible and unrestrained in their thinking and “who do things no-one else would have considered.”

All the participating scientists readily admit that it is impossible to have absolute objectivity in science. They are all aware of the likely impact of their own personal biases on the experimental outcomes as a consequence of observation and interpretation of data being heavily impregnated with theoretical assumptions. The following comments were made in response to our questions enquiring whether they usually have an idea or expectation of an experimental outcome, and whether that expectation could bias the results or the interpretation of experimental data.

Yes . . . I always perform a survey of related research done by other groups before we start the experiment. In most cases, the results of those earlier research studies may lead us to speculate the results of our experiments . . . Speculations not only bias the results or interpretation but also bias the strategy we employ for investigation. (Molecular biologist)

Yes, most certainly . . . say, if you map a piece of material for its content of gallium, indium and nitrogen. Since that is all you expect, you could potentially miss the presence of a trace amount of an additional element that has a major impact on the material properties. (Materials scientist)

All the scientists pointed out the impossibility of engaging in scientific inquiry without some theoretical speculation. In the absence of speculation, one would not know what to do, how to do it, or how to interpret the data. In other words, no theory-independent experiments are possible. Rather, every experiment is conducted within a particular theoretical matrix, which governs the investigator's perception of the problem(s), determines the experimental design, and influences the interpretation of the results. Thus, scientists often face a major dilemma: Expert knowledge of a field is essential to design the inquiry and interpret the data collected, yet it can seriously impact the integrity of the study, and if the theory is mistaken it can seriously mislead scientists by encouraging them to follow false trails. Both the astrophysicist and the cancer biologist commented that although it is inevitable that a scientist's preconceptions will influence both the design and the interpretation of an inquiry, the "truth" will eventually emerge (or biases will be recognized and corrected) when others, with different perspectives, investigate the same phenomenon or event.

Several respondents noted that standard protocols have been established in some research areas to reduce or eliminate bias due to prior expectations—for example, double-blind testing is commonly adopted in medical research. The medical geneticist stated very clearly that no experimental method is perfect, so no method can produce perfectly valid and reliable data. He pointed out that even relatively small variations in method can produce quite large differences in data, and even when the methods are procedurally identical, variations in data can still occur because of differences in the quality (reliability) of the instruments deployed or the bench skills of the technicians. In the following remarks by the experimental particle physicist, it is interesting to note his view that the checking of experimental results may be much less stringent for "expected and biased" observations than for "unexpected" outcomes.

It is typically much easier to convince your collaborators to publish something that agrees with the so-called "Standard Model." Yet particle physicists often want to announce something new (violating the "Standard Model"). But when they do so, they are extremely careful to check the results before they are satisfied about its reliability . . . do thousands of checks or calculations or simulations . . . Often, people stop or tend to stop checking when their results agree with the "Standard Model". (Experimental particle physicist)

WHAT SCIENTISTS TOLD US ABOUT THE ROLE AND STATUS OF SCIENTIFIC KNOWLEDGE

Theory-Laden Observation and Interpretation

When asked why different conclusions can be drawn about the extinction of dinosaurs from the same set of data (an item in the questionnaire), most of the participating scientists said that this situation is unsurprising. Indeed, knowledge generation requires scientists to "stretch their imagination and creativity" to construct explanations and theories to fit with existing observations. They noted that imagination is guided or even bounded by one's disciplinary training and experience.

The thinking of a biologist may be different from that of a geologist, physicist or archaeologist. Based on their knowledge or special interest in the field, each group might have focused differently from their point of view and come to different conclusions. (Cancer biologist)

The high-energy physicist gave us a similar example from the world of contemporary physics.

At present, general relativity and quantum mechanics, in their respective domains, are very accurate. [The former deals with massive objects, e.g. stellar objects, while the later deals with extremely small particles, e.g. electrons.] . . . However, we can still ask a question “what if a particle is both very heavy and small?” . . . Consider a black hole which is small but heavy, so that both quantum mechanical and gravitational effects can’t be neglected. What would happen? We agree to call a theory that can explain both regimes the *quantum gravity theory*. There have been many different versions and some have already been rejected . . . Currently two theories, *superstring* and *loop quantum gravity*, have remained as areas of active research alongside other new ideas . . . So far we have no empirical data to verify these theories. So it’s up to the researchers to make reasonable speculations. These two theories are well-established but tentative. Well-established in the sense that they have been around for about two decades and have still not been refuted by available data. Tentative in the sense that they are subject to change when more data reveal their inadequacy . . . other theories will emerge and replace the current ones when new experimental or observational data become available.

The scientists generally regarded diversity of interpretation as an essential stimulus to better theories, as illustrated by the molecular biologist.

Different interpretations may be a good thing because every mind is only a subset of the whole existing knowledge . . . and everyone’s subset is different. Using the same observations or data . . . (scientists) with different subsets will generate different explanations . . . it is the combination of all the interpretations that, after many years, may finally lead to the real picture. (Molecular biologist)

Nine of the thirteen scientists commented that the existence of more than one theory based on a set of observations could be a consequence of insufficient relevant data. The experimental particle physicist commented: “It is because there are not enough data or no relevant data to support one way or another. It is like $x + y = 3$ and everybody may pick their favourite x and y according to their own creativity to explain why $x + y = 3$.” He went on to comment that the arbitrariness of one individual’s suggestion has to be addressed when more relevant data become available. This scientist also remarked that he makes “guesses” in his research based on his belief in “the beauty of the universe,” but because this is not a logical move the conclusions have to be checked by other means and a logical argument has to be constructed before any other scientists will consider acceptance of the conclusions.

Although scientists were all aware of the theory-laden interpretation and its relationship to their creativity, they generally agreed that the differences in interpretation will be narrowed, if not resolved, by new evidence. The forms of new evidence can be new observations due to more careful data collection processes, more refined data due to advances in technology, or development of better theories to guide observation and interpretation of existing data.

Laws, Theories, and Models, and Their Tentativeness

In common with many school students, the experimental particle physicist, stem cell biologist, and cell biologist all subscribed to a hierarchical relationship between theories and laws.

As far as I understand, a scientific theory will become a scientific law when it is proved by a considerable number of experiments with reasonable accuracies. In physics, Einstein first published the theory of Special Relativity in 1905 but today it is as much a law as conservation of energy and momentum, as it has been proven by many experiments, and probably every day in our accelerator. (Experimental particle physicist)

For the experimental particle physicist, special relativity is one of the most fundamental pieces of science, and clearly what some science educators might regard as misuse of terminology concerning its status is not a serious impediment to productive research. Several scientists said that they had not seriously considered the meaning of terms such as “law” and “theory” before completing the questionnaire. But again, it does not seem to matter; a supposedly “inadequate understanding” of the terminology so revered by some philosophers of science, and by many science teachers and science education researchers, does not affect scientists’ ability to conduct research.

All participating scientists recognized the evolutionary or developmental NOS, with both theories and laws being subject to change. Indeed, accumulating new evidence to enrich and modify existing scientific knowledge and refuting a well-established paradigm is what all scientists aim and wish to achieve. Many scientists have moved well beyond the literal meaning of the terms. The astrophysicist, high-energy physicist, and molecular biologist all commented that the term “law” should no longer be used in science because it is a confusing term that indicates an unjustifiable status as “definitive and not subject to change.” They were adamant that all scientific knowledge, including “laws,” is subject to modification when there is appropriate evidence and a convincing argument.

The trend in science is to avoid using the word “law” . . . this word has its historical origins and meanings . . . In the past when people believed that something was right, it should always hold true. But as time goes on, different laws like Newton’s laws no longer stand . . . Even though we called them laws in the past, they are actually not laws at all. (Molecular biologist)

It is interesting to note that both the astrophysicist and the theoretical physicist hold almost the same view as the molecular biologist.

Since the beginning of last century, there has been no piece of scientific knowledge in physics called a law. They use terms like principles, theories or models. No one dares to call something a law . . . since the time of relativity and quantum mechanics . . . scientists seem to avoid using “laws” . . . People were really using a wrong name . . . they really believed that those laws, e.g. Gas Laws, Newton’s Laws, were laws because they would not change . . . They felt that the experiments carried out were sufficient to prove that the results were correct. Now we think that those experiments are not sufficient . . . We are now more humble that we don’t believe that we can find an absolute and definitive law of the universe in our lifetime. “Principles” and “rules” are currently used instead of “laws” among scientists. For example, Heisenberg’s Uncertainty Principle is of similar nature to many earlier physics “laws”. (High-energy physicist)

The high-energy physicist proceeded to talk about “theories” and their similarities to and differences from “laws.” He said that it is important for students to be aware that *established*

theories are just as robust as the so-called laws. There are, he said, three criteria for a good theory: *explanatory power*, *simplicity*, and *predictive power*. He then talked about *models*, which he sees as theories with a lower degree of rigor and robustness.

There are some rather loose or less rigorous theories that are normally of shorter life span. It is very common to have many different theories/models that try to explain a certain principle. Sometimes we [scientists] are aware of the tentativeness of certain trials to explain phenomena and those attempts were named, sarcastically by the proposers, “toy models”. To us, models are an entity which is less rigorous than theories and, of course, the less so for “toy models”. When more evidence was found to support a model, it would gradually be called a theory. In my view, the Big Bang is lying at the boundary of being a model and a theory. Both Big Bang model and Big Bang theory are currently used, though the tendency is inclined more to theory. (High-energy physicist)

Striving for simplicity (criterion 2 in the high-energy physicist’s characterization of theories) was seen as a powerful element of scientific theorizing by the astrophysicist:

If two hypotheses give you the same prediction, we tend to believe that the simpler one is the correct one . . . If there are two theories, one of which is more complex than the other one, we adopt the simpler one . . . This is consistent with our belief that the world is rational and easy to understand.

All the scientists echoed this commitment to the belief that the universe is both rational and understandable; without such faith, they said, scientific inquiry and attempts to build theories would be pointless.

Inevitably, discussion moved to the question of whether science is realist or instrumentalist. Is scientific knowledge a true description of the world or is it merely a convenient (and possibly fictional) construction for gaining a measure of control and predictive capability? Although the high-energy physicist sees a role for instrumentalist models (In some cases, scientists just construct models and say that *if these models are taken as true*, then interesting things would happen), his overall position is a realist one. His view that entities such as electrons are real because “we’re able to move individual electrons around” is essentially that is propounded by Hacking (1983). Indeed, all our scientists subscribed to the view that the predictive power and technological applicability of current scientific theories can be taken as strong evidence that in many respects we are getting closer to the truth about the universe. They seem to be saying that while a detailed explanatory structure itself may still be somewhat tentative and subject to elaboration and modification, the specific entities postulated within that theory have a real existence.

WHAT CAN WE CONCLUDE?

Scientists’ descriptions of their research and their day-to-day practices within the science community provide a view of science that can be compared and contrasted with the explicit and implicit images portrayed in school science textbooks and curricula, and with the views advocated by science educators (e.g., Lederman et al., 2002; Osborne et al., 2003). They also provide empirical evidence concerning the evolutionary or developmental character of NOS knowledge and the relationship between science and technology. Our data suggest very strongly that educators, curriculum designers, and teachers should recognize, if they have not already done so, that there is no single set of NOS elements, static with time and fitting all disciplines and contexts. The data also make us very wary of the crude categorization of NOS views as “naïve” or “adequate” on the basis of a questionnaire response or a generalized broad statement, and in the absence of adequate knowledge of the background and context

underlying the responses. For example, scientists' trust in using well-established scientific knowledge like special relativity in the search for newer knowledge, and their readiness to abandon those relatively loose and controversial theories accounting for the extinction of dinosaurs, is an illustration of the coexistence of "naïve" views of certainty and "adequate" views of tentativeness (Harding & Hare, 2000). Similarly, the "naïve" view that "science is universal" (held by all our scientists) coexists with the supposedly "adequate" view that science is socially and culturally embedded. Since the different views are situated in specific and well-understood contexts, they might be better categorized as *sophisticated understanding* of NOS, as suggested by Elby and Hammer (2001).

Our data provide some "from the horse's mouth" remarks to reinforce efforts to dispel the several prevalent myths about the absolute objectivity of science, the universality of its methods, and the certainty of the knowledge it produces. These data have much of value to tell us about the design of laboratory and field activities and the design of case studies capable of projecting an authentic view of scientific practice.

Some Thoughts on Objectivity and Universality: Toward More Authentic Laboratory Work

Although it is now 20 years since Hodson (1986) urged teachers to acknowledge the theory-laden nature of scientific observation, it is still only rarely elaborated in science textbooks, and is often overlooked by both teachers and students. In contrast, its recognition within the scientific community represented by our sample was universal. It is our contention that the excessive emphasis on cookbook and verification-type practical work, implying a single correct answer to all problems, serves to perpetuate the myth that "seeing is believing." It can be countered by early exposure to activities specifically designed to emphasize the subjectivity of observation—for example, use of film and video material using a moving camera, optical illusions and instruments to extend observational possibilities, identification of objects by listening, smelling, and tasting (to reinforce the point that observation requires assumptions to be made and questions to be asked as a guide to the collection of data), and the use of puzzle boxes and "feely bags" (Hodson, 1986). Thereafter, laboratory activities should be presented in a way that emphasizes their theory embeddedness. It is still not common for teachers to discuss the ways in which experiments, as well as observations, are theory impregnated or to point out that we can only investigate what we have speculated about, and in terms of *how* we have speculated about them. In a sense, as our respondents repeatedly told us, theoretical assumptions bias the inquiry and prejudice the conclusions. In consequence, the notion of absolute scientific objectivity is a myth. Observational and experimental data do not "speak for themselves"; all data have to be interpreted. In consequence, and contrary to the views expressed in many science textbooks, there can be no absolutely decisive experiments. Our findings have much to say on these issues, including the ways in which modern technology has changed the way some scientists conduct their inquiries, particularly in the biological sciences. It seems to us that the science curriculum has yet to catch up with these changes. More frequent and imaginative use of technology-supported and technology-enhanced laboratory work (e.g., using computers to collect, manipulate and present data, or to monitor and control experiments) would paint a more authentic picture of contemporary science than many of the procedures that currently occupy curriculum time. It is also vital that we provide more inquiry-based and open-ended practical work in which different solutions for a given problem are both possible and acceptable.

Our respondents also reminded us of the tendency to accept knowledge claims more readily, and at a lower level of rigor, when they reinforce our expectations and/or serve

our interests. Recognizing this tendency is an important element of scientific literacy, but is largely absent from science curricula. Encouraging students to reflect on their own experiences in interpreting experimental data in the school laboratory could be instrumental in bringing about this realization and could lead to a fruitful discussion of error, bias, distortion and fraud in science, and the need for knowledge claims to be scrutinized from multiple perspectives (both theoretical and sociocultural).

The high-energy physicist's description of the way he does research and his elaboration of the demarcation between theoretical and experimental physics will be new and surprising to most school science students, with the revelation that he does not conduct experiments at all running counter to most students' views of scientific practice. Our data can contribute to a portrayal that is closer to real-world science practice: Researchers in different fields use quite radically different approaches (a point on which all the scientists agreed). Some scientists focus on experimental work, others on theoretical issues. Some scientists use experiments, others may use naturalistic studies, historical reconstructions, or computer simulation and modelling tools. Despite the resounding message from scientists that context determines method of inquiry, many science teachers continue to instill belief in a common "scientific method"—a myth that is reinforced by the prominence given to "*the scientific method*" in the introductory chapters of science textbooks. It is common for a page or two to be set aside for a description of "what scientists do," usually presented in terms of a sequence such as observation, generalization, hypothesis, experiment, and theory. The notion of a fixed, all-purpose approach is then reinforced by dozens of laboratory reports in which students are required to emphasize each step of "the scientific method." Furthermore, making a hypothesis is usually regarded as an essential component of this stepwise generation of scientific knowledge (Watson, Goldsworthy, & Wood-Robinson, 1999) and is a prominent focus of standard assessment instruments. In short, hypothesis generation is usually regarded by science teachers as an essential component of experimentation, and because scientific inquiry is commonly regarded as solely experiment driven, students come to regard hypothesizing as a *sine qua non* of scientific inquiry. Our data can do much to address this serious misunderstanding of much of contemporary scientific practice. Our data also reveal that inductivist approaches, for so long derided by philosophers of science as logically invalid and impractical (see Chalmers, 1999), are alive and well in contemporary science. Indeed, they are considered essential in some fields as a means of building up a large database from which speculation can begin.

There is no doubt that the term "experiment" has high status in school science and many students believe that experiments constitute the only route to scientific knowledge. Indeed, teachers commonly refer to all activities occurring in the school laboratory as "experiments," regardless of their purpose and whether they are presented as teacher demonstrations or hands-on work by students (Hodson, 1988). Interestingly, the astrophysicist drew a distinction between meaningful "experiments" in science (for generating new scientific knowledge) and meaningful "experiments" in science education (for bringing about learning). Our view is that students should be aware of this distinction and the role of some laboratory activities in school science lessons as *theatre*—that is, providing evidence for what science holds to be stable, established knowledge. At the very least, we should make clear to students that laboratory and field activities can be designed to provide experience of phenomena and events, demonstrate an idea, principle or theory, or assist the acquisition of a particular laboratory skill. They can be conducted to make a measurement, establish a precise conceptual relationship, test a hypothesis, manipulate variables, collect data, or just "to see what happens when . . ." Focusing attention on these different motives will also help students to appreciate that scientists also have a range of motives for their laboratory and field activities.

Some Thoughts About Creativity and Imaginations, and the Construction of Theories and Models: Toward Case Studies of Authentic Practice

Another common myth among science students is that “science is procedural rather than creative” and that the “standard procedures” of science have priority over the individuality of the investigating scientist. The science curriculum sometimes suggests that scientific experimentation is a fairly straightforward business. In practice, experimental inquiries are subject to continuous monitoring and continuous modification (even reorientation) as scientists struggle to find a robust method. We were reminded by the medical geneticist that the idea of the perfect experiment is an illusion. We were reminded by several scientists that the fluidity of the inquiry stage is subsequently replaced by a much stricter and more controlled stage during which the sequence of purpose, design, findings, and conclusions is rationally reconstructed for public scrutiny prior to submission for publication. The continuing absence of any meaningful description of the historical development of scientific knowledge from many school textbooks, together with excessive emphasis on learning the products of scientific inquiry, not only undermines understanding of the development of scientific knowledge, but also it devalues the role of the individual in its generation. We believe that students will appreciate as well as benefit from the scientists’ remarks about different experiences and theoretical assumptions leading to different conclusions regarding the same data, and their comments about the key role of intuition and aesthetics in science. This is not an argument for abandoning emphasis on careful, dispassionate accumulation of data in favor of engaging students solely in creative leaps of imagination. Both are essential components of science, and the presence of both elements in our portrayal of NOS issues serves to remind us that we need both reliable technicians and creative theory builders and innovators. While all the scientists emphasized the need for creativity and imagination at *all* stages of an inquiry (before, during, and after data collection), they also claimed that science is more objective than other disciplines because of its basis in empirical data, the cross-checking nature of the peer-review process and the open reporting mechanism of journal publications and conference presentations. Part of that peer-evaluation process is close critical scrutiny of (i) the methods employed in generating data and (ii) the chain of argument leading from data to conclusions.

We found our discussions with scientists about laws, models, and theories particularly thought provoking. In general, they expressed significantly different views from those commonly adopted by science educators, which McComas (1998) summarizes as follows: “Laws are generalizations, principles or patterns in nature and theories are the explanations of those generalizations” (p. 54). It seems that many scientists have only a “loose understanding” of terms such as *theory*, *model*, *principle*, and *law*. However, they have no difficulty in expressing how these different knowledge items are used differently for description, prediction, or explanation. The evolving meaning of some of the terms highlighted by these scientists suggest that instead of being overly concerned about precise definitions, science teachers should be assisting students to judge the status of each piece of scientific knowledge in the context of its use. In that sense, it would be more useful to ascertain whether a piece of scientific knowledge is simply a qualitative description of phenomena and events, a statement of a particular phenomenological relationship in mathematical terms, a means of making predictions or obtaining a measure of control, or an attempt to explain the mechanism underlying phenomena and events. The ability to understand the function of a piece of knowledge and, crucially, being able to use it appropriately and productively, is more important than “proper” recital of definitions.

It is noteworthy that our scientists were unanimous in adopting a realist position regarding the status of scientific knowledge, even though they may use models of various kinds in an instrumental role as calculating devices or as tools for thinking as they move toward realist theories. In other words, scientists play both a realist game and an instrumentalist game, as determined by their immediate purpose. They develop theories when they aim to explain and describe the real world; they concoct convenient models when they seek no more than a quick and accurate calculation or prediction. What we have in mind for the school science curriculum is a similar position that enables students to be *critical* realists, capable of evaluating the status of a particular knowledge item and using it effectively in either an instrumentalist or a realist capacity, as the situation demands.

In recent years, the topic of models and modelling has generated considerable interest among science educators (Gilbert, 2004; Gilbert, Boulter, & Rutherford, 1998a, 1998b; Greca & Moreira, 2000), an interest that can be categorized into three principal areas of concern:

- the particular models and theories produced by scientists as explanatory systems;
- the ways in which scientists utilize models as cognitive tools in their day-to-day problem solving, theory articulation, and theory revision;
- the role of models and modeling in science pedagogy.³

Our intention is to use the questionnaire and interview data collected from scientists to design case studies that illuminate, first, the ways in which scientists use and develop models through the course of an investigation, and second, how consensus is reached in favor of a particular model or theory through a process of argument, counterargument, and negotiation. The data from which these community aspects of practice will be presented in a subsequent article. What we have in mind is an approach that emphasizes the discipline- and context-specific nature of scientific practice, as advocated by Rudolph (2000, 2003), Dagher and BouJaoude (2005), and Samarapungavan et al. (2006).

We will leave the final word on the desirability of NOS in the curriculum, and our case-based approach in particular, to the molecular biologist. Teaching about NOS, he said, can attract more young people to science, especially the more able students, because “it conveys a sense of excitement through its emphasis on creativity and intellectual endeavour.” This kind of understanding is also important for citizenship education because “it teaches students not to believe everything they are told and to have the confidence to work things out for themselves.” We can think of no better justification for the curriculum we are developing.

The authors gratefully acknowledge the 13 scientists who kindly devoted their precious time to be our informants.

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³ Focus three has a clear parallel with the idea of laboratory work as theater for bringing about specific conceptual acquisition and development.

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