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Reconceptualizing STEM Education

Edited by Richard A. Duschl and Amber S. Bismack

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The Central Role of Practices

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Edited by Richard A. Duschl and Amber S. Bismack

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Richard A. Duschl
To Stephanie, we are there, and I am so pleased to have you at my side and as my guide.

Amber S. Bismack
To Brian, thank you for your support and encouragement, and I am so happy to spend life hand in hand with you.

CONTENTS

PREFACE

The edited volume reports on the proceedings of the Waterbury Summit held during August 2013. Approximately 50 scholars gathered for three days to explore thematic practices associated with learning and teaching STEM disciplines—Science, Technology, Engineering, and Mathematics. The participants included Penn State faculty and graduate students and nationally recognized scholars brought together to examine K-16 STEM education. Names, bios, and the Summit sessions appear immediate after the Preface. The broad goal was to articulate research and development goals with respect to the reform agendas that advocate a shift to practices in STEM learning and teaching. The shift to practices is about getting students to use knowledge, to reason, to model, to explain, to critique, and to communicate. The Summit was a conversational conference interspersed with panels, discussions, and several social events providing ample time for exploring five thematic practices judged to be viable 'common ground' among the STEM disciplines.

The US *Next Generation Science Standards (NGSS)* and the US National Research Council's *A Framework for K-12 Science Education* herald "a new vision of science in education." The *Framework* and *NGSS* set out a comprehensive agenda for the reform of science and engineering education coordinated around three dimensions: Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. The new agenda has implications for 1) the redesign of preK-12 education for alignment of curriculum-instruction-assessment, 2) STEM teacher education and professional development, 3) post-secondary STEM education, 4) informal STEM education, and 5) graduate studies in STEM education. Hence, the audience for the book is preK-16 education stakeholders nationally and internationally. Additionally, and importantly, there are poorly understood implications for how policy decisions will be impacted and including instruction about the empirical nature of the development—the technical specificities of drilling, the chemical composition of fracking fluid, and so forth—is not enough to address these deep-seated ambivalences, and thus calls into question the appropriateness and comprehensiveness of such an approach.

Merely integrating these concepts into the curriculum in an unproblematized way cannot do justice to the seriousness of what is at stake for youth and educators within these dilemmas. In this sense, this case raises important questions about how educators are called on to conceptualize the scientific literacy that they are meant to develop and enhance in their students. In what ways is this conceptualization sensitive to the complex relationship between human sustainability and ecological sustainability? Rather than treating science solely as a value-free, empiricist activity, our findings suggest that educators may be better served by integrating issues related to scientific ethics and the weighing of values and social ends in dilemmas presented within the practice and use of science: a fundamentally interdisciplinary and "systems-based approach" to STEM education (Duschl, Bismack, Greeno, & Gitomer, this volume) that incorporates analyses of not only physical systems, but how those physical phenomena, systems and processes may interact with human systems, and in turn what the implications are for social, environmental, and economic sustainability, local and global. In the end, these analyses involve questions not only for empirical physical and social sciences, but basic *ethical* questions about what constitutes a good society and how we might achieve it.

It is very unclear, within the current policy regime of common standards and high-stakes assessments, whether educators possess—or believe they possess—sufficient autonomy to incorporate such approaches into their development of student STEM literacy. The cost of not doing so, however, is to leave youth and educators to wrestle with these issues individually and largely outside the school context rather than engaging collectively and critically on topics that are controversial and locally relevant, and yet nonetheless are deeply embedded within and have critical implications for global environmental and social sustainability.

Notes

1. This chapter was written with support from the Penn State College of Education Waterbury Summit. Data used in this manuscript were gathered in studies funded by the Penn State Marcellus Center for Outreach and Research, The Penn State Children, Youth and Family Consortium, and the Center for Rural Pennsylvania. We want to acknowledge the assistance and contributions of Leland Glenna and Brandn Greene in gathering some of the data discussed in this chapter.
2. Unconventional gas reserves typically refer to gas found *within* geologic formations (rather than trapped and contained by them) such as shale and sandstone. Because the gas is trapped within the shale layer, unconventional gas extraction typically relies on the use of horizontal drilling and hydraulic fracturing (Wilber, 2012).
3. Intermediate units are regional organizations unique to Pennsylvania, which serve multiple school districts in providing educational support and services.

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DEFINING A KNOWLEDGE BASE FOR REASONING IN SCIENCE

The Role of Procedural and Epistemic Knowledge

Jonathan Osborne

Introduction

The focus of many educational systems is rooted strongly in a belief that an understanding of science is so important that it should be a feature of every young person's education (American Association for the Advancement of Science, 1989; Confederacion de Sociedades Cientificas de España, 2011; Fensham, 1985; Millar & Osborne, 1998; National Research Council, 2012a; Sekretariat der Ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (KMK), 2005; Taiwan Ministry of Education, 1999). Many of these documents and policy statements give pre-eminence to an education for citizenship. Likewise, the emphasis in the Programme for International Student Assessment (PISA) frameworks is on science for citizenship seeking to assess the competency of 15-year-old students to become informed critical consumers of scientific knowledge—a competency that all individuals are expected to need during their lifetimes (Organization for Economic Cooperation and Development [OECD], 2012). Drawing on the example of PISA, this chapter explores what kinds of knowledge bases are required to engage in such reasoning.

Scientific literacy in PISA 2015 is defined by the three competencies:

1. Explaining phenomena scientifically;
2. Evaluating and designing scientific inquiry; and
3. Interpreting data and evidence scientifically.

Clearly these competencies lie at the heart of what it means to reason scientifically and require knowledge of science or *content knowledge*. The second and third competencies, however, require more than a knowledge of what we know. Rather, they depend on an understanding of how scientific knowledge is established and the degree of confidence with which it is held. Historically, specific calls have been made for teaching about what has variously been called "the nature of science" (Lederman, 2007), "ideas about science" (Millar & Osborne, 1998) or "scientific practices" (National Research Council, 2012a). Within PISA, the 2006 framework operationalized this aspect of science using the term "knowledge about science." Recognizing and identifying the features that characterize scientific inquiry does, for instance, require a knowledge of the standard procedures of the diverse methods and practices used to establish scientific knowledge—which in this chapter will be called *procedural knowledge*. However, these competencies also require an understanding of the rationale for the common practices of scientific inquiry, the status of the knowledge claims that are generated, and the meaning of foundational terms such as theory, hypothesis, and data—essentially what might be called *epistemic knowledge*. Procedural and epistemic knowledge are necessary to identify questions that are amenable to scientific inquiry, to judge whether appropriate procedures have been used, to ensure that the claims are justified, and to distinguish scientific issues from matters of values or economic considerations. What then might be the constructs of procedural knowledge and epistemic knowledge? How might they be defined and how might they be demarcated from each other? This chapter offers an exploration of these constructs and a rationale for their importance. It will argue that such ideas help to clarify the forms of knowledge that should be an outcome of any K-12 science education.

What Knowledge Bases Are Needed for Scientific Reasoning?

Hill (2008) has argued that the societies that sustain their competitive edge will be "post-scientific" societies. In such societies, highly valued skills will be the ability to draw on a range of disciplinary knowledge, to think creatively and to evaluate new ideas in a critical, reflective and rational manner. Employers will require individuals who, while having a core understanding of scientific and technical principles, have the ability to communicate and synthesize knowledge in an original manner. Likewise, experts invited to a National Research Council (NRC) symposium in 2007 to explore the nature of the competencies required for the future workplace argued that the ability to solve problems creatively, sophisticated communication skills, self-management, and systems thinking would be needed (NRC, 2008). More recently, the NRC report *Education for Life and Work* (National Research Council, 2012b) stresses the development of three domains of competence—the cognitive, the intrapersonal, and the interpersonal. Central to the first of these is developing the ability to undertake the complex cognitive processes of critical thinking, non-routine

problem solving, and constructing and evaluating evidence based arguments. Taken together, such arguments suggest that the valued competencies of the future will be the higher order reasoning abilities of evaluation, synthesis, and critique.

As Hill argues, if developing these competencies are to be a feature of science education, then it is important to "be certain that we emphasize what we want, for we shall surely get what we emphasize" (2008, p. 9). Yet, when it comes to the skill of reasoning scientifically, science education has suffered from a lack of clarity about "what we want." Despite the lip service that is paid to developing the ability to think critically, the picture that emerges from several studies is one where the prevailing classroom pedagogy in science focuses on transmission of a body of knowledge, is dominated by the use of closed, authoritative dialogue, and provides little opportunity to explore the domain of ideas in a critical and reflective manner (Lyons, 2006; Osborne & Collins, 2001; Tobias, 1990; Weiss, Pasley, Smith, Banilower, & Heck, 2003). Weiss et al. found that only "14 percent of lessons nationally having a climate of intellectual rigor, including constructive criticism and the challenging of ideas" (2003, p. 54), suggesting that a substantial gap exists between the rhetoric and the reality about the goals and possible value of any education in science. However, in approaching the task of identifying the knowledge base required for scientific reasoning in K-12 science education, I argue that two problems have confounded the field: first, is the disjuncture between domain-specific and domain-general conceptions of scientific reasoning; and second, a lack of clarity about the role of knowledge in scientific reasoning.

The first problem is a product of the many attempts to define scientific reasoning that historically have placed an emphasis on scientific reasoning as a *domain general* concept. One version of this perspective is seen among psychologists who commonly take a "nothing-special view" (Simon, 1966) arguing that general reasoning abilities account for the main characteristics of scientific reasoning, and are more *transferable*. Klahr and Simon (1999) acknowledge that domain-specific aspects are the basis for "strong methods" within the sciences, but claim that these only have limited value because they apply to well-defined contexts and problems. Instead, they contend that, when scientists move into new areas and meet ill-defined problems, general strategies or "weak methods" are the most important forms of initial reasoning. And it is these that should be taught to non-scientists—as "weak methods" can be deployed in new contexts external to science where the majority of students will be for their working lives.

The contrary argument, however, has been made both within psychology and science education. Perkins and Salomon made a seminal argument (Perkins & Salomon, 1989) that "general heuristics that fail to make contact with a rich domain-specific knowledge base are weak" and that "a domain-specific knowledge base without general heuristics . . . is brittle" (p. 24). Within science education, Passmore and Stewart (2002) have argued that "scientific practice is discipline specific" (p. 187) as do Duschl et al. (this volume) pointing to the specific role of models and quantitative reasoning. Sandoval (2003), too, concludes from his analysis of student explanations of Galapagos data "that epistemic and conceptual understanding are tightly interrelated" (p. 48).

I, too, wish to add to the argument that defining scientific reasoning as a domain general cognitive skill is both flawed and unsustainable. It is flawed because it misrepresents the nature of scientific reasoning as, while individuals in everyday situations may use reasoning akin to that of scientists, such forms of reasoning cannot be used to *define* what is distinct about scientific reasoning. Similarly, arguments for the value of teaching domain-general reasoning within science are unsustainable because general reasoning does not *have to* be taught in science. Other school subjects may be better at teaching, for example, moral reasoning, decision-making, and problem solving skills. A logical consequence then is that a conception for *domain specific* scientific reasoning is needed if we wish to claim that science education can foster higher order thinking skills required by contemporary society.

What, for instance, are the domain-specific entities used when reasoning within the domain of science? Essentially what is the role of knowledge in scientific thinking? The answer is the second critical problem that needs to be addressed in order to establish a better construct of scientific reasoning. Undoubtedly, a factor that has changed over the past six decades is the development in our understanding of what we mean by knowledge and reasoning—a development that can be illustrated by the changes that have occurred in Bloom's taxonomy of cognitive processes (1956) when compared to the revised version offered by Anderson and Krathwohl (2001). Bloom and his colleagues did not separate knowledge from knowing. Moreover, they did not include any form of "meta knowledge" (Krathwohl, 2002). Anderson et al., in contrast, split reasoning into two dimensions, a knowledge dimension and a cognitive process dimension, and use not one but four categories to describe their knowledge dimension: factual knowledge, conceptual knowledge, procedural knowledge, and metacognitive knowledge. Likewise, Li and Shavelson (2001) have used a similar framework splitting knowledge into declarative knowledge (knowing what), procedural knowledge (knowing how), schematic knowledge (knowing why), and strategic knowledge (knowing when, where, how knowledge applies)—a perspective which was influential in developing the NAEP 2009 framework for assessment in science (National Assessment Governing Board, 2008). The common point in these and other examples is that they alter the way we conceptualize the relationship between knowledge and reasoning. That is, what used to be explained as a generic "reasoning skill" linked only weakly to a body of undifferentiated knowledge is now dependent on a set of distinctive

aspects of domain-specific knowledge of "what we know," "how we know," and "why it happens."

That reasoning within any domain requires domain-specific knowledge is also shown by Schunn and Anderson (1999) who point out how, lacking such knowledge, undergraduate subjects "did not use theories in designing their experiments" and "did not relate their results to their experiments," concluding that what the scientist has acquired "is not just a matter of general reasoning ability" (p. 368). Likewise, Koslowski (1996) in her critique of earlier work by Deanna Kuhn argued that in reasoning scientifically, "theory and data are both crucial, and theory and data are interdependent. Sound scientific reasoning involves bootstrapping: considerations of theory or mechanism constrain data, and data in turn, constrain, refine, and elaborate theory" (p. 86). More recently, Duschl (2008) has argued for the need to balance conceptual goals—that is a knowledge of the content with epistemic and social goals. However, to date, little has been done to define the nature of the domain-specific, procedural, and epistemic elements that might constitute the goals of any science education. For instance, given the epistemic importance of peer review or of double blind trials in establishing scientific claims, should some knowledge of these procedures be a basic element of all students' education in science?

Attempts to Define the Knowledge Base for Scientific Reasoning

More or less, ever since its inception as an element of the school curriculum, one of the arguments for the value of science education has been its value for training the "general faculties of mind" (Huxley, 1854). Then, as perhaps now (Roschelle, Bakia, Toyama, & Patton, 2011), this claim was contentious leading Faraday to ask "what is their [the natural sciences] effect on the mind? . . . or what does the mind learn by that training?" (Layton, 1973, p. 173). Similar sentiments were expressed nearly 50 years later by Layton who argued that "the question of content or process, subject matter or method of inquiry, is a recurring and still unresolved issue in the relatively short history of school science teaching" (p. 174). And, I would argue, still unresolved.

It is impossible, however, to review or discuss all the attempts that have been made to solve the challenge of operationalizing what we might wish to teach about scientific reasoning. Indeed, that would require a full history of science education and beyond, as the answers developed within science education also draw on developments in science studies and the learning sciences (as demonstrated by Duschl & Grandy, 2012, 2008). Rather what is presented here are some of the notable attempts to address the challenge and the ways in which they have succeeded or not. Importantly, the goal is not so much to criticize the failings of past approaches to teaching scientific reasoning but rather to learn from past mistakes—very much in the tradition of Santayana's sentiments that "those who forget the lessons of history are condemned to repeat the mistakes of the past."

Teaching Scientific Reasoning through Inquiry

A familiar and long-stranding approach to teaching scientific reasoning is to present learning as a process of inquiry. As long ago as 1759, Edmund Burke wrote that (Burke, 1909):

> I am convinced that the method of teaching which approaches most nearly to the method of investigation, is incomparably the best; . . . it tends to set the reader himself in the track of invention, and to direct him into those paths in which the author has made his own discoveries (p. 12).

In the teaching of science, Armstrong, the most well-known English proponent of this approach, argued for what he termed the "heuristic method," which "involves placing our students as far as possible in the attitude of the discoverer-using methods which involve their *finding out*, instead of being merely told about things" (Armstrong, 1902).

Joseph Schwab, who chaired the US development of the Biology Curriculum Studies in Science (BCSC) project, extended and elaborated the rationale for this approach to the teaching of scientific reasoning arguing that the teaching of science should be an "enquiry into enquiry!" (Schwab, 1962). The BSCS textbooks were committed to what Schwab called a "radical departure [from] conventional patterns" by embedding all content as an invitation to enquiry (Schwab, 1962, p. 39). An analysis of the textbooks would suggest that in print this objective was realized. Over 50 percent of the text was dedicated to helping students approach investigative problems—a feature which the most recent edition of the BSCS Human Approach textbook sustains (Chiappetta & Fillman, 2007).

Similar notions are articulated 30 years later in the National Science Education Standards (National Research Council, 1996) which argued that teaching science called for more than teaching science as a process and the specific skills of observing, experimenting, and inferring—a statement that suggests the authors were aware of the inherent problems of the process approach. Instead it offered a vision of science teaching where "inquiry is central to science learning" in which:

> students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations. In this way, students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills (p. 23).

In one sense, such an argument is seductively attractive. It offers a conception of learning science that embodies the practice of science itself. But it is flawed in two ways. First is the flaw embodied in Ryle's distinction between "knowing how" and "knowing that" (Ryle, 1949). Learning science through a process of inquiry develops an extensive knowledge of the procedures required to produce new scientific knowledge e.g., "knowing how," but what it does not develop explicitly is a meta-level knowledge of the rules, procedures, and values that science uses and why these are required—what might be termed "epistemic knowledge." Thus a student may engage in a discussion over competing interpretations of a given data set, but such practice does not necessarily develop the knowledge and understanding that critique is essential to the successful construction of knowledge in science (Ford, 2008; Longino, 1990; Popper, 1962), or an understanding of the role and function of peer review. Rather, developing an explicit knowledge of the role of any practice requires a meta-level reflection on the practice itself that must be taught explicitly (Lederman, 2007; Monk & Osborne, 1997; Peters, 2009). Similar points can be made about building students' explicit knowledge of the procedural techniques that science uses. In short, simply engaging in a practice predominantly develops a body of tacit expertise (Polanyi, 1958). There is, for instance, little evidence that scientists hold sophisticated models of science. In contrast, there is a considerable body of evidence that school science leaves its students with naïve understandings of science because it fails to explicitly explore the nature of the discipline (Driver, Leach, Millar, & Scott, 1996; Lederman, 1992; Solomon, Scott, & Duveen, 1996).

Schwab did attempt to present a description of the epistemic and procedural constructs that govern scientific inquiry, but limited it to the "kind of conclusion, kind of data, and mode of verification" (p. 76), which are intrinsic to science. All sciences, Schwab argued, were reliant on a set of classificatory schema (taxonomic knowledge); measurement science which he described as "simple quickly describable patterns of enquiry"; causal science which seeks to show how one entity in a "system of mutually interacting and mutually determined parts acts as a concerted whole" (Schwab, 1962, p. 89); and analogical science which is the attempt to explain by inventing mechanisms not directly accessible to observation. The latter form of reasoning required the development of models and theories. Thus Schwab's work can—and should be seen as an attempt to define the knowledge bases required for scientific reasoning and address the lack of an explicit recognition. However, Schwab's work only managed to identify in general terms the epistemic constructs that are the foundation of scientific reasoning. Likewise, his work did not recognize that participating in inquiry required a body of procedural knowledge of specific constructs intrinsic to inquiry such as the notion of an independent/dependent variable, types of error, reliability and validity and more. Thus, in failing to identify sufficiently the forms and features of the knowledge on which scientific reasoning depended, his work lacked the insights necessary to build a deeper picture of what it means to reason scientifically leaving the second problem unresolved.

The second flaw in the argument for inquiry-based teaching of science is the conflation of the *doing* of science with the *learning* of science (Chinn & Malhotra, 2002; Roth, 1995) when the two are activities distinguished by their *differing* goals. In particular, that the goal of doing science is the discovery of new knowledge, whereas the goal of learning science is to comprehend the major features of the scientific landscape, to appreciate the intellectual achievement these ideas represent, and to understand how such knowledge has been derived. To suggest that inquiry—the major methodological tool of the scientist—can also be the major procedure for learning science is to make a category error akin to suggesting that learning to understand and appreciate music can only be achieved through playing an instrument—leaving no role for the education of the critic or music lover who has never played.

To his credit, this was not an error that Schwab made. Schwab did draw a distinction between presenting science as a product of a process of inquiry and using inquiry itself for learning and teaching—arguing that the inquiry curriculum was "by no means the only version nor necessarily the most desirable version in all schools for all students" (Schwab, 1962, p. 71). However, this was a distinction that others failed to recognize seeing "inquiry as central to science learning" (NRC, 1996). Retrospectively, the emphasis on teaching science through inquiry can be seen as an attempt to offer an account of what it means to do science that is more commensurate with contemporary scholarship. However, without a consideration of what forms of knowledge were required, and hence what kind of conceptual understanding such practice might seek to achieve, such efforts left the teaching of scientific reasoning akin to a ship lost at sea with no landmarks for guidance. For instance, Spillane et al.'s comment that "it is common for science teachers to report, for example, that they use inquiry in their classroom. Yet people can mean very different things by such a report" (Spillane, Reiser, & Reimer, 2002, p. 416). And as the recent NRC *Framework* commented "attempts to develop the idea that science should be taught through a process of inquiry have been hampered by the lack of a commonly accepted definition of its constituent elements' resulting in widely divergent objectives" (NRC, 2012a, p. 44). Part of the failure to develop a coherent or common understanding is, I would argue, due to a lack of clarity about what type of knowledge any given practice seeks to develop.

The Recognition of Procedural Knowledge

An initiative that led to the conception that there was more to "knowing science" than content knowledge came from the UK *Assessment for Performance Unit* (APU) project. This project, begun in the 1970s and lasting for 10 years, was an attempt to measure the performance of a representative sample of the educational systems in English, Mathematics, Science and Modern Foreign Languages akin to the US NAEP program. The group in charge of science developed an assessment framework (Murphy & Gott, 1984) that was "process oriented" and focused on students' performance on written and practical laboratory tasks. From the data of students engaging in empirical inquiry, the APU developed the notion of "procedural knowledge" which they distinguished from a "process skill" conceptualizing the relationship between the two as akin to that between "strategies and tactics" (Black, 1990)—a knowledge of common strategies being a body of explicit declarative knowledge whilst tactics were equivalent to the skills required to use such strategies judiciously.

Building on these findings and, in part as a response to Millar and Driver's critique of the process approach (Millar & Driver, 1987), Gott and Murphy (1987) argued against seeing investigation or inquiry simply as a "process skill." Instead, they sought to define inquiry as an "activity." Within such an "activity," they argued, students made use of both *conceptual* and *procedural* understanding. The latter was a knowledge and understanding of scientific procedures, or "strategies of scientific inquiry, "such as holding one factor constant and varying the other when controlling variables" (p. 13). This insight had emerged from an analysis of their results where they found that much of the variation in student performance on tasks could not be explained solely on the basis of an absence of appropriate conceptual knowledge e.g., the lack of a suitable model of the system being investigated. Rather, it was accounted for by "procedural failures," i.e., students not holding the necessary procedural knowledge. This finding led the APU to the conclusion that "the major influence on performance on this task is the availability to the child of certain relevant items of knowledge" and that "carrying out a scientific investigation, then, is primarily a display of understanding, and not of skill" (Gott & Murphy, 1987, p. 244).

Consequently, Gott and Murphy argued for the explicit teaching of procedural knowledge suggesting that "we must accept the need to develop an explicit underpinning [procedural] knowledge structure in the same way that we have developed such a structure for conceptual elements of the curriculum" (1987, p. 52). Developing this notion in a later paper, Gott and Mashiter (1991) explicitly presented *procedural knowledge* as the "missing element" that could form the basis of a theoretical response to Millar and Driver's (1987) question of "what develops" in their critique of the process approach. As such, it offered a new theoretical perspective that made the scientific reasoning required for empirical inquiry and critique knowledge-based rather than skill-based. This rationale was then developed further into a more complete framework, or "taxonomy," for procedural knowledge to be taught in school science (Duggan, Gott, Lubben, & Millar, 1996; Gott & Duggan, 1996) which the authors describe as "concepts of evidence" (Gott, Duggan, & Roberts, 2008).

Evidence of the importance of procedural knowledge in scientific reasoning has come from many research studies. One important study was the *Procedural and Conceptual Knowledge in Science* (PACKS) project that sought to identify what knowledge students actually apply when solving practical investigative tasks (Millar, Lubben, Gott, & Duggan, 1994). This research used written items to probe students' procedural knowledge and compared their performance with that of the investigative tasks. Correlation was high, indicating that what was tested in the written items accounted for 50 percent or more of the variance in practical tasks. The research also revealed "misconceptions" among students about scientific methodology. Many students expressed what Schauble, Klopfer, and Raghavan (1991) refer to as an "engineering framework" and interpreted the goal of the practical investigative task as an empirical test of the best solution rather than a means of testing a scientific hypothesis. Another important outcome was to identify levels of understanding from simple to advanced procedural knowledge (Lubben & Millar, 1996) thereby answering Millar and Driver's question of what develops. Thus the work of Gott and his colleagues identified a body of knowledge other than domain-specific conceptual knowledge required for scientific reasoning.

Such knowledge is essential for the 2nd competency in the PISA framework of evaluating and designing scientific inquiry (OECD, 2012). Evaluating any design requires questions to be asked about what variables have been identified, whether they have been appropriately controlled, how many measurements to take, how the potential for measurement error was minimized and more. Likewise, interpreting data and evidence is dependent on some knowledge of the data collection procedures. What, for instance, is a double blind trial and what is the role of the placebo? PISA defines this competency as the ability to:

TABLE 15.1 The Competency of Designing and Evaluating Scientific Inquiry (PISA, 2012)

Describe and appraise scientific investigations and propose ways of addressing questions scientifically demonstrating the ability to: • Identify the question explored in a given scientific study; • Distinguish questions that are possible to investigate scientifically; • Propose a way of exploring a given question scientifically; and • Evaluate ways of exploring a given question scientifically.
Describe and evaluate a range of ways that scientists use to ensure the reliability of data and the objectivity and generalizability of explanations.

Thus, to engage in critical deliberation about the validity and reliability of the data produced by any specific scientific inquiry, students need knowledge of:

- Concepts of measurement and of systematic observation;
- Ways of assessing and minimizing uncertainty;
- Mechanisms to ensure the replicability and accuracy of data;
- Concepts of variables;
- Common ways of abstracting and representing data using tables, graphs, and charts;
- Control of variables strategy and its role in experimental design and randomized controlled trials; and
- Appropriate designs for different scientific questions (e.g., experimental, field based or pattern seeking).

As such, this list represents an upper anchor for any progression in learning. What the steps and levels are for acquiring such knowledge and understanding is an important research topic for empirical investigation.

Although procedural knowledge offers an interesting alternative to the process skill paradigm, there remains one substantive problem; the claim that knowledge in scientific reasoning is *either* conceptual *or* procedural. Whilst such knowledge does address the goals of "knowing that" and "knowing how," "knowing why"—the epistemic goal—is not addressed. Duggan and Gott (2002) attempted to solve this problem by organizing concepts of evidence for scientific reasoning into "inner and outer layers," measuring and interpreting data concepts at *the core,* and understandings about science practices at the periphery. This approach, however, ignores the insights emerging in the past few decades where scientific knowledge is presented as the product of a set of both social and *epistemic* practices (Kuhn, 1962; Latour & Woolgar, 1986; Traweek, 1988). That is, students need to understand the features of scientific practice and their *epistemic* roles for procedural knowledge to have any meaning.

Scientific argumentation and epistemic knowledge

One feature emerging from the normative descriptions offered by philosophers (Kuhn, 1962; Lakatos & Musgrave, 1970; Nersessian, 1989; Popper, 1962) and from the ethnographies by sociologists (Latour & Woolgar, 1986; Pickering, 1983; Traweek, 1988) is a recognition that scientists rely on informal arguments of the type outlined by Toulmin (1958). In such arguments, claims are supported by data whose significance is established through warrants and underlying assumptions. As Quine (1951) pointed out, scientific theories do not exist in isolation but in competition with other theories. Hence, they must be argued for. Establishing the validity of any hypothesis requires both a deductive argument from premises to conclusion, as well as an inferential argument to the best explanation (an abductive argument). A notable example is in the paper by Watson and Crick (1953) proposing the structure for DNA where the authors begin not by arguing *for* their proposed solution but rather why two competing models were flawed. Likewise, Darwin's argument for the theory of evolution is both a hypothetico-deductive argument of the consequences of random mutation and natural selection and an inferential argument that it provides the best explanation for the diversity of species. Yet science education fails to make this kind of meta-level knowledge about the role and type of argument in science—what I wish to term epistemic knowledge explicit.

One significant attempt to remediate this omission was made by Driver, Newton, and Osborne (2000). Drawing on the ideas of science educators (Duschl, 1990), social epistemologists (Fuller, 1997), rhetoricians (Taylor, 1996), and science communicators (Gregory & Miller, 1998) who all argue for presenting science as a process in which scientific knowledge is socially constructed, and in which "discursive activity is central to the process of science" (p. 290), Driver et al. presented an influential paper making the case that, as argument was a core feature of science, it should likewise, be a central feature of science education. Arguing that "if students are to assimilate these norms [of argument], they also need the experience of rehearsing them for themselves" (p. 304), they advanced a case that engaging in argument had a role in developing conceptual understanding, enhancing investigative competence, and understanding the epistemology of science.

Another missing element is that of the role of explanatory models in science. Over the last 50 years, various scholars have identified that a key heuristic for scientific reasoning is building and using models of natural systems (Cartwright, 1983; Giere, 1984; Suppes, 1960). Models offer conceptual representations that enable deductive inferences about the behavior of systems or causal mechanisms. For instance, the wave model of light not only offers an explanation of how light can appear to bend round corners in terms of the concept of diffraction, but also predicts the behavior of light in thin films. Models and modelling are, therefore, "a signature of much research in the sciences" (Nersessian, 2008, p. 59), standard part of its practice and, hence, should be a core feature of science education—a point emphasized by Schauble (1996) who argued that "the goal of scientific reasoning is not primarily the formulation of inductive generalizations, but rather the construction of explanatory models" (p. 103). The philosopher Ron Giere, too, places the construction of models as a central feature of explaining scientific reasoning (Giere, 1984; Giere, Bickle, & Mauldin, 2005). Recognition within science education was marked in 2000 when the edited volume "Developing Models in Science Education" appeared (Gilbert & Boulter, 2000). Further contributions to developing model-based curricula can be found in Wells, Hestenes, and Swackhamer (1995), Van Driel and Verloop (1999), Grosslight, Unger, Jay, and Smith (1991) and Smith, Snir, and Grosslight (1992).

What this body of scholarship suggests is that the breadth and complexity of scientific reasoning requires the recognition that *epistemic knowledge* taught explicitly to students is a third element of a knowledge of science. Moreover, over the past two decades the field has been wrestling with how to incorporate such elements. The movement to address the nature of science specifically (Lederman, 1992; Matthews, 1989) can be seen as one attempt to incorporate some aspects of epistemic knowledge. Likewise, Millar and Osborne's notion of "ideas-about-science" (1998) or the more generic term "how science works" are other formulations of what is a distinct body of knowledge *about science itself*. Coupled with empirical evidence suggesting that nature of science knowledge is a significant element of any science education (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003), such arguments have led to epistemic knowledge becoming a more prominent feature of contemporary curricula. Indeed, the 2007 version of the English national curriculum (Qualifications and Curriculum Authority, 2007) included a specific component entitled "How Science Works" while the *Framework* outlines eight scientific practices which should be an essential element of K-12 science (NRC, 2012a) though notably this document does not define any specific elements of epistemic knowledge.

The 2015 PISA assessment framework (OECD, 2012) does incorporate epistemic knowledge as consisting of two components—a) a knowledge of the constructs and defining features essential to the process of knowledge building in science, and b) the role of these constructs in justifying the knowledge produced by science. The features of the first component are a knowledge of:

- The nature of scientific observations, facts, hypotheses, models and theories;
- The purpose and goals of science (to produce explanations of the material world) as distinguished from technology (to produce an optimal solution to human need), what constitutes a scientific or technological question and appropriate data;
- The values of science e.g., a commitment to publication, objectivity and the elimination of bias; and
- The nature of reasoning used in science e.g., deductive, inductive, inference to the best explanation (abductive), analogical, model-base.

Whilst the features of the second component are a knowledge of:

- How scientific claims are supported by data and reasoning in science;
- The function of different forms of empirical inquiry in establishing knowledge, their goal (to test explanatory hypotheses or identify patterns) and their design (observation, controlled experiments, correlational studies);
- The function of a scientific hypothesis in enabling a testable prediction;
- How measurement error effects the degree of confidence in scientific knowledge;
- The use and role of physical, system, and abstract models and their limits;
- The role of collaboration and critique and how peer review helps to establish confidence in scientific claims; and
- The role of scientific knowledge, along with other forms of knowledge, in identifying and addressing societal and technological issues such as the prevention of disease, the supply of sufficient water, food, and energy and climate change.

Undoubtedly, such a list is partial and open to debate. Notably, though, the role of modelling is incorporated in this list. In addition, the lack of specificity in this list inevitably leaves it open to the critique of what exactly is meant. Does the failure to elaborate these constructs make them of little value? One response to this criticism is that the PISA framework states that only an understanding of what might be reasonably expected of an average 15 year old should be tested. While that does not answer the question, it does set limits. Moreover, I would argue that such a list performs the important first step of identifying and pointing towards what kind of knowledge is an essential requisite for scientific reasoning and is an important contribution to the solution of the second problem—the lack of an adequate recognition of the knowledge bases needed for scientific reasoning.

The latest vision of science elaborated in the *Framework* sees science as consisting of a set of social practices which take place in three "spaces of activity": a space for experimentation and investigation; a space for developing explanations, hypotheses, and models which enable prediction; and a space for critique and evaluation—elements which are captured by Figure 15.1 and which form the basis of the model in the chapter on practices (NRC, 2012a). The notable feature of this representation of science is that the role of modelling and the development of theoretical explanations are seen as being core features of science, as is argumentation from evidence. In that sense it goes a long way to remediating the common perception that the central practice of science is experimentation.

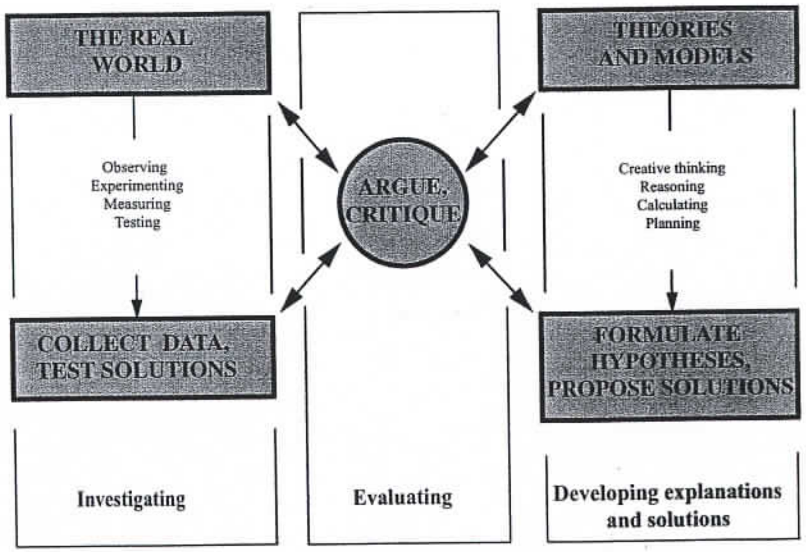

FIGURE 15.1 Scientific reasoning model; combining Klahr and Dunbar (1988) and Giere (2006)

Nevertheless, whilst the map is a representation of forms of scientific activity, it does not provide a vision of what it means to reason scientifically. To be a representation of scientific, as opposed to historical or other forms of reasoning, such activity is dependent on domain-specific disciplinary ideas, *procedural* and *epistemic* knowledge. While the *Framework* elaborates in great detail the first of these, the latter two are notable by their absence. Could sustained engagement in scientific inquiry and the practices of science develop the kind of knowledge of science that we might seek to attain as Duschl and Grandy (2012) argue? Such an argument is based on a view that knowledge is acquired by immersion in a practice. The first counter argument is that there is little evidence that the professional scientists develop a deeper philosophical or sociological understanding of science than the educated layperson. Lakatos memorably commented of scientists' that "most scientists tend to understand little more *about* science than fish about hydrodynamics" (Lakatos, 1970, p. 148). Second, the time available for compulsory science education is insufficient to develop epistemic and procedural knowledge without explicit reflection on practice and its purpose in attaining the goals of science. The goal of science education is not to develop a high level of proficiency with the practices of science, but rather, to use the engagement in a limited repertoires of scientific practices as a means of building as deep a knowledge and understanding of the content of science, the procedures that it commonly uses to achieve its goals, and the epistemic justification for their use as time permits. If so, then it is important that we should define the features of procedural and epistemic understanding that should be the outcome of any education in science and teach them *explicitly*. Asking students to engage in scientific practice must be seen as a means to an end. And, if so, it helps to be clear about what those ends might be and to have a model of science that has a degree of philosophical credibility (that is an accepted normative description) and a sociological and psychological credibility (in that it fits best with the empirical data). Only when armed with this kind of understanding can the teacher act as an effective guide to why any practice is an essential activity of science.

In summary, scientific reasoning may therefore be seen as requiring the use of three distinct types of knowledge: knowledge of scientific facts, theories, and concepts (content knowledge); procedural knowledge; and epistemic knowledge. It is, perhaps, self-evident that generating a scientific hypothesis requires content knowledge; less evident are the findings of research (Reiner & Gilbert, 2000) that suggest that epistemic knowledge or resources also plays a crucial role in its production. Experimentation, similarly, is not just a matter of knowing *how* to get reliable data—which is a procedural issue—but also *why* this is important—which is an epistemic issue. It is true that sometimes one phase of activity may be solved without involving all types of knowledge. Klahr (2000), for instance, has shown that his subjects generated correct hypotheses to a problem without considering any experimental data. But scientific reasoning is never dependent solely on *one* type of knowledge.

Conclusion and Implications for Practice

This chapter commenced by identifying two problems that have troubled science education for a long time and that, without resolution, will continue to cause confusion and, at worst, sustain poor pedagogic practice. The first problem identified was the lack of a definition of the domain-specific knowledge requirements for scientific reasoning. The appeal of a domain-general definition is that it would suggest that the capability developed by scientific reasoning is readily transferable to other areas. However, only if we can identify why any form of reasoning is unique to science can we defend the teaching of reasoning *in* science rather than in *any* subject. If, after all, reasoning is essentially domain-general, the argument that science offers some kind of unique training of the mind is flawed.

The second problem was the failure to identify the specific forms of knowledge needed for scientific reasoning. Finley (1983) saw the absence of domain-specific knowledge as the main challenge to Gagné's skills-based rationale for the teaching of science. The overemphasis on the domain-general at the expense of the domain-specific has inhibited the practice of science education itself. Nowhere has this emphasis been more evident than in psychologists' use of *content-lean tasks*, in which the aim has been to study reasoning without "interference" of the candidate's conceptual understanding—see for instance, D. Kuhn (1991).

The response to these two problems has been to provide a rationale for scientific reasoning which recognizes that it is a domain-specific activity that requires three categories of domain-specific knowledge: scientific conceptual knowledge, procedural knowledge, and epistemic knowledge. These forms of knowledge are seen as a requirement for the 3 competencies required to be scientifically literate within the new PISA framework for 2015, and the chapter has sought to elaborate a rationale for some of the features of procedural and epistemic knowledge. This is not to say that all cognitive skills are context-bound, but rather that the development of all reasoning must begin within a context—an argument first made by Perkins and Salomon (1989).

Engaging in scientific reasoning commonly requires at least two, if not all, three types of knowledge. The challenge for the field then is how such bodies of knowledge might be best taught. For instance, recent research (Allchin, 2011; Ford, 2008) challenges the common assumption that students first must learn the declarative features of such knowledge and then apply this in authentic situations. Ford (2008) conceptualizes the learning underlying experimental and epistemic understanding as a "grasp of practice," suggesting that they are learned by *enculturation* rather than explicit teaching. However, such an approach places too much emphasis on the acquisition of knowledge through practice and is challenged by evidence that suggests that such ideas need to be explicitly addressed (Lederman, 1992; Peters, 2009). School science does not have the luxury of time that is afforded the graduate student. Rather, engaging the student in any scientific practice should be seen as an opportunity to illuminate explicitly the nature and complexity of the knowledge and skill that is required of the professional scientist, just as the novice's attempts to play any musical instrument are used to build an understanding of what is necessary for a polished performance.

What then are the implications for science education? Only an account captured by Figure 15.1 or something similar demonstrates why it is theories and models that are the "crowning glory of science" and not empirical inquiry. In short, science is fundamentally about the ideas we have developed to explain the material world (Oakeshott, 1933). The phenomena are events to be explained but not the key feature of science itself. Second, it requires science educators to establish some kind of consensus about the features of epistemic and procedural knowledge that should be an essential element of the K-12 science curriculum.

The argument here has been that the failure to place scientific reasoning at the center of the science curriculum can be attributed to the lack of clarity of its role and function in learning science. To borrow from Kuhn's notion of *paradigms* within a discipline, this portrayal of the confusion and range of competing perspectives within science education resembles what Kuhn calls the period of *pre-science*, the period in which there is clearly a phenomenon of interest, worthy of study, but no coherence or agreement about its theoretical framing within the community. Present knowledge is now such that the time has come for the establishment of a period that is more akin to *normal science* where we can coalesce around a more unified vision of the nature of scientific reasoning and its role and function within any science education, and the knowledge bases required. This will require a consensus about its main characteristics and a common language within the community. Only then, can we offer students a less-distorted account of the scientific enterprise.

Note

1. Schwab chose to spell enquiry with an 'e'.