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Teaching Scientific Practices: Meeting the Challenge of Change

Jonathan Osborne

Abstract This paper provides a rationale for the changes advocated by the Framework for K-12 Science Education and the Next Generation Science Standards. It provides an argument for why the model embedded in the Next Generation Science Standards is seen as an improvement. The Case made here is that the underlying model that the new Framework presents of science better represents contemporary understanding of nature of science as a social and cultural practice. Second, it argues that the adopting a framework of practices will enable better communication of meaning amongst professional science educators. This, in turn, will enable practice in the classroom to improve. Finally, the implications for teacher education are explored.

Keywords Scientific practices · Teacher education · Teaching science

Introduction

Many science teacher educators will be trying to make sense of the changes to science education required by the Framework for K-12 Standards (National Research Council, 2012) and the Next Generation Science Standards (Achieve, 2012). A major innovative element is the shift from teaching science as inquiry to teaching science as a practice. Chapter 3 of the NRC Framework provides a rationale both for what the practices are and their significance in the learning of science. Questions that immediately come to mind are why the shift from inquiry? What is the underlying vision of science and what new elements need to be emphasized with the focus of practices? What are the implications for the ways in which we educate pre-service and in-service teachers? This paper attempts to offer an answer to some or all of those questions exploring the argument for the practice based approach and the implications for teacher educators.

J. Osborne (✉)
Graduate School of Education, Stanford University, Stanford, CA, USA
e-mail: osbornej@stanford.edu

Why Change?

The dominant paradigm in US science education has, ever since the publication of the National Science Education Standards (National Academy of Science, 1995), been that science should be taught as a process of inquiry. What is the dissatisfaction with this approach? One argument is that a basic problem with the emphasis on teaching science through inquiry is that it represents a confusion of the goal of science—to discover new knowledge about the material world—with the goal of *learning* science—to build an understanding of the existing ideas that contemporary culture has built about the natural and living world that surround us. From the latter perspective the goal of science education is fundamentally different. It seeks not to create new knowledge, but rather to help students understand a body of existing, consensually-agreed and well-established *old* knowledge. Thus, the flaw in the argument for inquiry-based teaching of science has been a conflation of the *doing* of science with the *learning* of science (Chinn & Malhotra, 2003; Roth, 1995) when, in reality, the two are activities distinguished by their *differing* goals. And, 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. Instead a knowledge and understanding of science is best acquired through applying our knowledge and understanding of how humans learn (Bransford, Brown, & Cocking, 2000; Donovan & Bransford, 2005) and a deep understanding of the nature of the discipline.

A second problem with the teaching of science through inquiry has been the lack of a commonly accepted understanding of what it means to teach science *through* inquiry. For many teachers and for many students the notion of inquiry has been conflated with the idea that inquiry requires students to handle, investigate and ask questions of the material world. Hence any activity that is of a ‘hands-on’ nature can be considered to fulfill the basic requirement of this pedagogic approach. In this form, inquiry is seen not as a means of developing a deeper understanding of the nature of scientific inquiry but rather as a means of serving the pedagogic function of illustrating or verifying the phenomenological account of nature offered by the teacher (Abd-El-Khalick et al., 2004). The result is that the goals of engaging in inquiry have been conflated with the goals of laboratory work such that, in the eyes of many teachers, the primary goal of engaging in inquiry is not to develop a deeper understanding of the whole process of inquiry but to provide a means of supporting their rhetorical task of persuading their students of the validity of the account of nature that they offer. If there is an alternative focus, it tends to be on the performance of the skills required to do inquiry—and then predominantly on the manipulative skills for successful experimentation (knowing how)—rather than the analysis and interpretation of the data or an understanding about inquiry and its role in science (knowing that or knowing why). At its worst, the product is cookbook laboratory exercises where students simply follow a series of instructions to replicate the phenomenon.

So the answer to the question posed about what are the problems of teaching science through inquiry is that the conception was poorly articulated and, as a consequence, poorly communicated. Moreover, the lack of a professional language that defines and communicates the categories of activity that students should experience—that is a workable classification of educational practice—undermines

Table 1 A comparison of the abilities to do scientific inquiry (National Research Council, 2000) with the set of scientific practices found in the Framework for K-12 Science Education

Fundamental abilities necessary to do scientific inquiry (Grades 5–8)	Scientific practices
Identify questions that can be answered through scientific investigations	Asking questions and defining problems
Design and conduct a scientific investigation	Developing and using models
Use appropriate tools and techniques to gather, analyze and interpret scientific data	Planning and carrying out investigations
Develop descriptions, explanations, predictions and models using evidence	Analyzing and interpreting data
Think critically and logically to make the relationship between evidence and explanations	Using mathematical and computational thinking
Recognize and analyze alternative explanations and predictions	constructing explanations and designing solutions
Communicate scientific procedures and explanations	Engaging in argument from evidence
Use mathematics in all aspects of scientific enquiry	obtaining, evaluating and communicating information

the professional practice of teaching science. For instance, Bowker and Star (1999) show how the introduction of such systems in other professions e.g., nursing has enabled comparability across sites, made specific activity visible, and provides a structure and control of the activity so that there is some consistency across sites. Thus the confusion in science education surrounding terms like 'science literacy' and 'inquiry' ultimately undermines our ability to communicate meaning and establish a reserved professional language. A focus on practice and, in particular an elaboration in terms of 8 specific practices makes an important contribution to addressing this problem.

The National Science Education Standards of 1996 provide an elaborate list of the abilities necessary to do scientific inquiry. Indeed, these look remarkably similar to the list of eight practices to be found in the recently published *Framework for K-12 Science Education* (National Research Council, 2012) shown in Table 1.

The obvious question that must then be asked is in what sense are these different? How is the notion of teaching science through inquiry any different from asking students to engage in scientific practices? The answer to this question, it will be argued, comes from a greater clarity of goals about what students should experience, what students should learn, and an enhanced professional language for communicating meaning.

Seeing Science as a Practice Based Activity

The notion of science as a set of practices has emerged from the work of the science historians, philosophers, cognitive scientists and sociologists over the past 40 years. The key turning point was the work of Kuhn (1962). Kuhn showed that science was undertaken by a community of scientists whose work was dominated by a set of values and normative criteria—some of which were socially negotiated—that is a community of practitioners engaged in specific, consensually agreed practices. The body of scholarship that followed has illuminated how science is actually done, both in the short term (e.g., studies of activity in a particular laboratory or a program of study) and historically (e.g., studies of laboratory notebooks, published texts, eyewitness accounts) (Collins & Pinch, 1993; Conant, 1957; Geison, 1995; Latour & Woolgar, 1986; Pickering, 1995; Traweek, 1988). Seeing science as a set of practices has shown that theory development, reasoning and testing are components of a larger ensemble of activities that include networks of participants and institutions (Latour, 1999; Longino, 2002); specialized ways of talking and writing (Bazerman, 1988); modeling, using either mechanical and mathematical models or computer-based simulations (Nercessian, 2008); making predictive inferences; constructing appropriate instrumentation; and developing representations of phenomena (Latour, 1986; Lehrer & Schauble, 2006a).

Developing students' understanding of the epistemic basis of science—how we know what we know—requires students to study or engage in the common practices of science (Duschl & Grandy, 2013). Only then will they begin to understand how scientists establish credibility for the claims that they advance. In short, what do scientists *have to do* to establish reliable knowledge (Ziman, 1979). Developing such an understanding requires that we have an overarching picture of the primary activities in which scientists engage. Such a model is required to understand the role and significance of any one practice. The model in Fig. 1 taken from the Framework for K-12 Science offers one such picture. This model has emerged from empirical psychological studies of practice and normative philosophical studies of what scientist do. From such studies, Klahr et al. (1993) concluded that the practice of science involves three main 'processes', which they refer to as *hypothesizing*, *experimentation* and *evidence evaluation*. These terms convey the idea that science requires a 'process' of activity using reasoning which leads to the solution of three 'problems' (developing hypotheses, generating data to test the hypotheses, and evaluating and coordinating evidence to draw a conclusion), and that these processes happen in phases. This description of science resembles Popper's (1972) separation of *conjecture* and *refutation* of scientific hypotheses but adds a third aspect, evidence evaluation. Klahr et al., however, did not develop their model on philosophical grounds. Rather, their model of *Science Discovery as Dual Search* (SDDS) was presented as an account of their empirical findings when observing the reasoning that their subjects used to solve simulated scientific inquiry tasks in psychological experiments. Thus, rather than a philosophical argument that reflected underlying normative principles, their conception of science was a product of empirical observation of university students and school children, the youngest being school children in elementary schools, actually doing science.

What is of interest is that Giere et al. (2006), provide a similar model from a philosophical perspective that also suggests three phases of inquiry as a structure for scientific reasoning. This model, however, has been derived from philosophical case-studies of authentic science, such as Crick and Watson's development of the DNA model, and explains how science works *in principle*. Such a normative account describes the set of actions embodied in scientific practice, how science

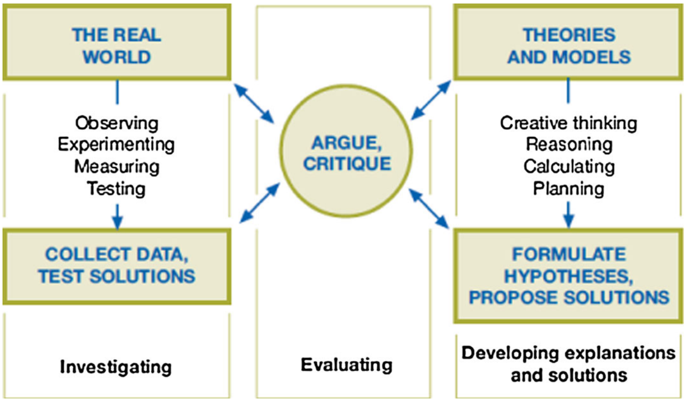

Fig. 1 A model of scientific activity; combining Klahr and Dunbar (1988) and Giere et al. (2006). This diagram was first published in Osborne (2011) and subsequently in the Framework for K-12 Science Education (NRC, 2012)

should be conducted, and the values that participants in the scientific community share. Both Giere et al. (2006) and Nersessian (2002) see to be the construction of explanatory models of the material world.

The fact that a group of philosophers and a group of psychologists—that is scholars from two distinct disciplines—independently arrived at similar models is significant implying that there *is* some underlying structure to scientific activity. Taken together, these two models suggest that scientific reasoning has three distinct 'phases of activity'—experimenting (the activity of investigating the material world); hypothesis generation (the activity of developing explanations and solutions of what is observed and found); and evidence evaluation (the activity of evaluating both the data and the theories and models offered as explanations) which are identified by the nature of the specific types of problems to be solved, governed by a set of normative criteria set by the scientific community, and draw on distinctive forms of reasoning such as deduction, induction and abduction.

In what sense, though, is this model helpful to science education? The answer is that science begins with a question—which is always a subset of the primary question—'what is nature like?' Thus one of the key practices that scientists engage in is the asking of questions. This form of activity constitutes part of what is represented by the left side of Fig. 1. Observations in their turn, however, generate a causal question of 'Why does it happen? Such a question engenders the scientists' creative imagination, the construction of models and the production of explanatory hypotheses—the element of activity that is represented by the right side of Fig. 1. Such ideas must then be tested. The testing of ideas requires either the design of empirical investigations and the collection and analysis of data or both. Such data and the methodological procedures enable scientists to answer the third question of 'How do we know?' and 'How can we be certain?' However, achieving consensus and establishing the validity of such claims is reliant on argument and the critical evaluation of evidence.

In science there are ‘experimenters’ who work predominantly in the spaces of experimentation and evaluation but draw on the work of theoreticians who develop models and hypotheses which form the theoretical premises of their investigation. Conversely, there are ‘theoreticians’ who work predominantly in the space of hypothesis generation but draw on the critical evaluation of their colleagues and the data produced by the ‘experimenters’ to evaluate the validity of their theories. Thus, all scientists, whatever their disciplinary identity may be, are forced to engage in evaluation. Many scientists, of course, do not fall into either of these groups but in their research move fluidly between the three spaces.

Moreover, these spheres of activity are not self-evident. That is, someone coming new to science would not necessarily recognize these three problem spaces as the key features of the work of the scientist. Studies of young children (Driver, Leach, Millar, & Scott, 1996; Klahr & Carver, 1995; Millar, Gott, Lubben, & Duggan, 1995; Schauble et al., 1991) reveal that students often see science differently. These, and other studies, suggest that many students adopt a naive realist interpretation of scientific theories, seeing them as emerging from data. Younger students are likely to view experimentation as a process that is intended to lay bare or discover the facts of nature; older students are more likely to recognize the role of ideas in stimulating, directing and influencing the interpretation of experiments. The outcome is that too many students fail to see that it is really theories that are the ‘crowning glory of science’ Harré (1984); that science is fundamentally about *ideas* not experimentation; and that your name is preserved for posterity in science not for devising a new experiment but for developing a new theory.

The Centrality of Critique

Why is engaging in argumentation and critique so central to all science? As Ford (2008) has argued, its significance lies in the fact that the construction of knowledge is dependent on a ‘dialectic between *construction* and *critique*[1]’ (p. 404) where ‘critique motivates authentic construction of knowledge’. Ford’s view is that the critical spirit of science is founded first on a belief that any new claims to knowledge must be always be held up to the light for critical examination. The history of science is a history of mistakes. Hence either the data offered in support of the claim or the inference drawn from the data may be flawed; it this process that results in reliable knowledge. Ford’s insight is the recognition that critique has a similar role to play in the in the learning of science as well.

Why critique is important to scientific learning then can be understood by considering the process of learning as being metaphorically akin to weighing the two competing ideas—proposition A and proposition B. Initially, evidence might suggest they are of equal merit. Imagine then that good exposition, in the absence of critique, raises the credibility of A such that the weight of evidence for this proposition is twice as strong as the evidence for idea B. In the presence of critique, however, the credibility of the evidence for the alternative proposition B is halved as well. The ratio of credible evidence for A with respect to B now becomes four times

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[1] emphasis added.

as strong leading to a more secure and enduring understanding. The validity of this description is confirmed by a series of studies demonstrating that the opportunity to engage in critique leads to enhanced conceptual knowledge when compared with students who are not provided with such an opportunity (Ames & Murray, 1982; Hynd & Alvermann, 1986; Schwarz, Neuman, & Biezuner, 2000). Why then the virtual absence of critique and critical thinking from science education, both past and present? An absence which at least explains Rogers' comment that 'we should not assume that mere contact with science, which is so critical, will make students think critically' (p7) (Rogers, 1948). One of the arguments for the turn to practices is that it places the higher order skills of critique and evaluation at the center of teaching and learning science.

Why Practice?

More specifically, how will a focus on asking students to participate in scientific practice improve science education? First, it is not the primary function of school science education to train students to do science. Engaging in practice only has value if: (a) it helps students to develop a deeper and broader understanding of what we know, how we know and the epistemic and procedural constructs that guide the practice of science; (b) if it is a more effective means of developing such knowledge; and (c) it presents a more authentic picture of the endeavor that is science. Currently, there is little evidence that science education is achieving such goals. For instance, in their extensive observational survey of the teaching of science and mathematics in US, Weiss et al. (2003) found that only '14 % of lessons nationally having a climate of intellectual rigor, including constructive criticism and the challenging of ideas' (p54). Engaging students in scientific practices, it is argued, will make cognitive demands of a form that science education rarely does. Hence, asking students to engage in practice can improve the quality of student learning. How each practice assists is briefly discussed next.

Asking Questions

Questions drive the need for explanation and are the engine which drives all scientific research. As Asimov said the most profound statement in science is not 'Eureka' but rather 'That's funny…?' Only by asking relevant questions can students begin to understand the importance of their role in science. Engaging in this practice will, therefore, require opportunities to ask questions of what they observe and to refine their notion of what makes a good scientific question. The value of students' questions for learning has been emphasized by several authors e.g. (Biddulph, Symington, & Osborne, 1986; Chin & Osborne, 2008; Fisher, 1990; Penick, Crow, & Bonnsteter, 1996). Questions raised by students activate their prior knowledge, focus their learning efforts, and help them elaborate on their knowledge (Schmidt, 1993). The act of 'composing questions' helps students to attend to the main ideas and check if the content is understood (Rosenshine, Meister, & Chapman, 1996). More importantly, knowing what the question is gives meaning to science. Textbooks, for instance, are full of explanations but rarely begin by explicating the question that they are seeking to answer (Ford, 2006). As one one ascerbic student commented that ‘the problem with science is that it gives answers to questions you have never asked’.

Developing and Using Models

Models are needed in science because science deals with things too large to imagine such as the inside of a volcano, the solar system or the phases of the Moon (Gilbert & Boulter, 2000). Conversely, models are also needed to represent things which are too small to see such as a cell, the inside of the human body or the atom itself (Harrison & Treagust, 2002). Young children will begin by constructing simple physical models or diagrammatic representations (Ainsworth, Prain, & Tytler, 2011) but then at higher grades, models become more abstract and more reliant on mathematics. However, although some models are simply representational, such as the Bohr model of the atom or a model of a cell, other models can explain or enable predictions. Thus the bicycle chain model of an electric circuit not only explains why the electric light comes on instantaneously it also explains why, if the chain is broken, no light will come on. A more complex example is Maxwell’s mathematical model of electric and magnetic fields that correctly predicted the existence of electromagnetic waves travelling at the speed of light. As Lehrer and Schauble argue ‘modeling is a form of disciplinary argument’ that students must ‘learn to participate in over a long and extended period of practice’ p182 (Lehrer & Schauble, 2006b).

An important point is that the goal of engaging students in modeling is not just one of developing their understanding of the concepts of science. Rather it is to develop a form of metaknowledge about science—that is a knowledge of specific features of science *and* their role in contributing to how we know what we know. Essentially, what might be termed epistemic knowledge. For instance, asking students to construct models helps them to understand that the goal of science is not the construction of a picture that accurately depicts every aspect of nature but of a map which captures some certain features better than others just as the Google satellite map highlights different features from the two dimensional plan map.

Constructing Explanations

The construction of explanations, a third practice, makes similar demands to that of modelling. Many explanations in science are reliant on the construction of models so that the two practices are deeply inter-related. Commonly, students are the recipients of many explanations provided by teachers but rarely are they asked to construct explanations themselves (McRobbie & Thomas, 2001; Weiss, Pasley, Sean Smith, Banilower, & Heck, 2003). Yet work in cognitive science has demonstrated its value for learning (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, De Leeuw, Chiu, & Lavancher, 1994). Chi et al. postulate the reason that asking students to engage in explanation is effective is that, having articulated an incorrect explanation, further reading leads to the generation of a contradiction that will produce conflict. The outcome of such conflict will require metacognitive reflection and self-repair by the student if resolution is to occur.

Engaging in Argument from Evidence

The argument for a fourth practice—engaging in argument from evidence has already been made. For this practice too there is also a growing body of empirical evidence which points to improvements in conceptual learning when students engage in argumentation (Asterhan & Schwarz, 2007; Mercer, Dawes, Wegerif, & Sams, 2004; Sampson & Clark, 2009; Zohar & Nemet, 2002). For instance, Mercer et al. (2004) found that students who were asked to engage in small-group discussions significantly outperformed a group of control students in their use of extended utterances and verbal reasoning, features which are rare in formal science education (Lemke, 1990). Significant improvements were also produced in their non-verbal reasoning, and understanding of science concepts.

Again, a major goal of asking students to engage in argumentation must be to develop meta-knowledge of science. Foremost must be that all claims to know in science have to be argued for. From the idea that all objects fall with the same acceleration (in the absence of air resistance) to the idea that climate change is an anthropogenic effect, all claims require justification drawing on a body of data and warrants. Sources of error may be models that are flawed or data that are unreliable or fallible. The degree of confidence we hold in any idea is dependent on the minimization of error and the accumulation of a body of evidence over time. Nothing is held to be infallible. Rather there are only degrees of certainty.

The second goal must be to demonstrate that there are a range of forms of argument in science. There are arguments which are abductive[2] (inferences to the best possible explanation) such as Darwin's arguments for the theory of evolution; hypothetico-deductive, such as Pasteur's predictions about the outcome of the first test of his anthrax vaccine; or simply inductive generalizations archetypal represented by 'laws'. Moreover, arguments are necessary in all spheres of activity (Fig. 1) as there may be different experimental designs, alternative models, or contested interpretations of any data set each with their competing merits. From an educational perspective, the value of asking students to engage in argumentation is that it demands the higher order cognitive competencies of evaluation, synthesis and comparison and contrast (Ford & Wargo, 2011).

Planning and Carrying out Investigations

A functional understanding of the nature of science also requires students to be able to 'evaluate the design, practices and conduct of scientific enquiry' (OECD, 2012). Indeed, the PISA Assessment framework sees this as one of the three key competencies of the scientifically literate individual. Asking students to engage in the practice of designing empirical investigations to test a hypothesis is what best

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[2] Abductive arguments are also known as retroductive arguments.

develops such a competency. Yet evidence would suggest that this rarely happens. For instance, in a detailed study of two grade 8 classrooms, Watson, Swain, and McRobbie (2004) found that the quantity and quality of discussion surrounding their empirical enquiry was low concluding that:

> For the most part, students and teachers seemed to view scientific inquiry as learning to carry out a set of fixed procedures, which they were not expected to justify, and which could be used over and over again in the same ways in different inquiries. (p. 40)

Moreover, the exposure to a limited set of forms of empirical enquiry will not develop an understanding of broader repertoire of practice with which experimental scientists engage.

Analyzing and Interpreting Data

Observation and empirical enquiry produce data. Data do not wear their meaning on their sleeves. First, data may suffer from either systematic or random errors such that some values are simply outliers and should be eliminated from any data set. Second, there may be systematic errors in the data set. A good contemporary example of the latter is the tendency to publish only positive findings for drug trials and not the negative findings—what is known as publication bias (Lehrer, 2010; The Economist, 2013). As a consequence, the evidence for the efficacy of a drug can appear significantly better than it is in reality[3] and the consequences can be so serious that lives are lost.

What matters is not the collection of the data itself but its analysis. For instance, in many 6th grade science class you can observe students measuring the boiling point of water. But to what end? As an exercise to ascertain a value that has already been determined much more accurately by others its purpose is highly questionable (Collins & Pinch, 1993). As an activity to develop students' facility with a thermometer it too has little value given that it takes little skill to read a digital thermometer. However, given that students' readings may vary considerably, the much more interesting question is how can we resolve the uncertainty? What methods exist and which of these are appropriate in this context? Since there are plural answers to the latter question, its resolution requires the application of a body of domain specific procedural knowledge that serves as the warrants to justify the most appropriate result. There has to be room in the teaching of science for data sets that are ambiguous and where the meaning is less than self-evident. Being able to interpret data requires procedural knowledge of why there is error in measurement, the concept of outliers and the need to summarize the main features of the data.

The PISA assessment framework for the 2015 Assessment (OECD, 2012) sees the competency to 'interpret data and evidence scientifically' as another of the three core competencies of a scientifically literate person. Such a competency can only

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[3] Ben Goldacre offers an excellent discussion of this issue in a TED talk (http://www.ted.com/talks/ben_goldacre_what_doctors_don_t_know_about_the_drugs_they_prescribe.html).

develop by asking students either to gather their own sets of data, or use secondary data sets, and then establish and justify the best interpretation.

Using Mathematical and Computational Thinking

Another characteristic feature and practice of science is the use of mathematical and computational thinking. Science education often delays the mathematization of scientific ideas. Rather there is a belief that it is more appropriate to develop a qualitative understanding of ideas and that too much early attention may develop an algorithmic facility but no deep understanding of science. The consequence is that 'science curricula within the 5–16 age range appear to be seeking to manage without mathematics, or at least to function on as little as possible' (p. 146) (Orton & Roper, 2000). As Orton and Roper argue, the lack of mathematics in the curriculum gives an impression of science that is 'somewhat dishonest'. Gill (1996) argues that 'biology teachers should stop telling themselves (and their students) that biology doesn't need mathematics' such that they arrive at College with a false impression and are taken aback.

Mathematics and computational thinking *are* central to science enabling the representation of variables, the symbolic representation of relationships and the prediction of outcomes. As such mathematics supports the description of the material world enabling systematic representation that is the foundation of all scientific modeling and the clear communication of meaning. Thus mathematics serves pragmatic functions as a tool—that is both a communicative function, as one of the languages of science, and a structural function, which allows for logical deduction. Mathematics and numerical representation are the basis of all measurement in science. Numerical data have formalized ways of representation which enable the identification of a result in which there is more confidence (mean, mode and median) and ways of showing variation using a range of tables, charts or stem and leaf plots. Moreover, there is a body of research conducted in the learning sciences that shows that it is possible for young children to appropriate a range of mathematical resources which help formalize their interpretation and representation of their data. For instance in an extensive program of work over 15 years (Lehrer & Schauble, 2006a, 2012), these researchers have shown how students learned to "read" shapes of distributions as signatures of prospective mechanisms of plant growth and conducted sampling investigations to represent repeated growth (Lehrer & Schauble, 2004).

For too many teachers of science, however, mathematics is not something that is central and core to practice of science. Many, perhaps, operate with the vaccination model of mathematics, much as they do with literacy, that it is not their responsibility to educate students in the mathematics (or the literacy) required to understand science. And if students have not been vaccinated, there is little that they, the teacher, can do. But if mathematics is not a core feature of what happens in science classrooms the nature of science will be misrepresented. Avoiding the opportunity to use mathematical forms and representations *is a failure* to build students competency to make meaning in science. Hence opportunities to engage in the practice of mathematical and computational thinking are an essential experience in the teaching and learning of science.

Obtaining, Evaluating and Communicating Information

This practice, the eighth practice in the Framework for the K-12 standards, is one which is core to all science. Literacy is not some kind of adjunct to science—it is *constitutive of science itself* (Norris & Phillips, 2003). Indeed, contrary to the popular image which perceives the major practice of science to be one of 'doing experiments', Tenopir and King (2004) found that engineers and scientists spend more than 50 % of their time engaged in reading and writing science.

In short, writing and arguing are core activities for *doing* science (Lemke, 1990; Jetton & Shanahan, 2012). Indeed, as Norris and Phillips (2003) point out, the fundamental sense of literacy in science is the ability of an individual to construct meaning through interaction with the multiple forms of semiotic communication that are used *within* the discipline of science. Indeed, the 5 major communicative activities of science can be seen as writing science, talking science, reading science, 'doing'[4] science and representing scientific ideas—an idea which is represented by Fig. 2.

To develop some kind of insight into the activity of science, science education must offer students the opportunity to experience and practice a broad range of discursive and literate activities and scaffold students in the specific forms of disciplinary literacy required (Pearson, Moje, & Greenleaf, 2010; Shanahan & Shanahan, 2008). As the work of systemic functional linguists has pointed out, the forms of communication within a discipline, while reliant on basic literacy, are often specific *to* the discipline (Fang, 2006; Halliday & Martin, 1993; Lemke, 1990; Martin & Veel, 1998; Schleppegrell & Fang, 2008). Shanahan and Shanahan (2008) and Jetton and Shanahan (2012) argue for the concept of 'disciplinary literacy'—that is the ability to decode and interpret more complex forms of text, to recognize the nature and function of genre specific to the discipline, and to use author intent as a frame for a critical response.

The importance of developing students' disciplinary literacy skills in science classes has been recently come to the fore with the advent of the Common Core State Standards for English Language Arts and Literacy in Science (CCSS-ELA) (Common Core State Standards Initiative, 2010). By including literacy standards for each K-12 grade-level about informational and expository texts, the creators of the CCSS-ELA have acknowledged the recommendation of numerous researchers: that language should play a more prominent role in science instruction (Bazerman, 1998; Halliday & Martin, 1993; Lemke, 1990; Norris & Phillips, 2003; Pearson et al., 2010; Wellington & Osborne, 2001).

Another major challenge posed by the language of science, however, is not just the domain-specific vocabulary but also the use of 'academic language'—the form of language that is used to attain "conciseness, achieved by avoiding redundancy;

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[4] In one sense, any of these activities could be said to be 'doing science'. In this chapter, the term 'doing science' is used to refer to the act of engaging in empirical inquiry.

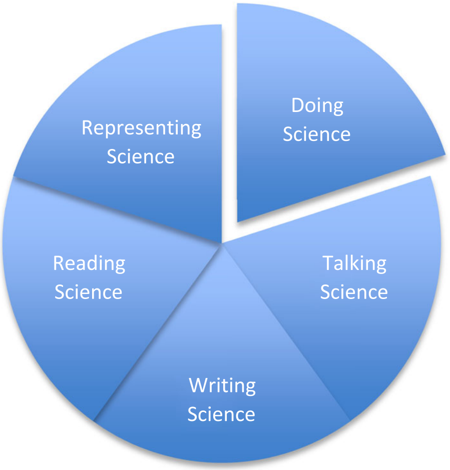

Fig. 2 The major activities of science

using a high density of information-bearing words, ensuring precision of expression; and relying on grammatical processes to compress complex ideas into few words" (p. 450) Snow (2010). Yet, traditionally, science teachers have not paid much attention to text (Wellington & Osborne, 2001), operating rather on the notion that there is nothing particularly distinctive about the genres in which science is communicated. The outcome of the view that literacy is a peripheral feature of science results in science teachers who lack a knowledge about "the vital role [that] literacy plays in enhancing rather than replacing science learning" (p. 462, Pearson et al., 2010) and, thus, teachers fail to mentor students in the necessary literate practices (Barton, Heidema, & Jordan, 2002) which would help them read science.

The Implications for Teacher Education

Developing students' capability with a practice is not just a case of developing a skill. The ability to engage in practice is best seen as a competency (Koeppen, Hartig, Klieme, & Leutner, 2008) which is reliant on a body of knowledge which is specific to the context. The primary purpose of engaging in practice is to develop students' knowledge and understanding required by that practice, how that practice contributes to how we know what we know, and how that practice helps to build reliable knowledge. Knowledge of how we know (knowing how) is reliant on a developing a body of procedural knowledge or concepts of evidence (Gott et al., 2008). Knowing why such practices are necessary is dependent on what I choose to call epistemic knowledge. Such disciplinary knowledge, I would argue, is a necessary element of any competent teacher of science. What, then are its primary features?

Procedural Knowledge

Gott and Murphy (1987) 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 enquiry’ 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 the research team had 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 them 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: p244). As a consequence, Gott and Murphy argued for teaching of procedural knowledge explicitly 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 (p. 52)”.

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, 1995). This research used written items to probe students’ procedural knowledge and compared their performance with that on the investigative tasks. Correlation was high, indicating that what was tested in the written items accounted for 50 % or more of the variance in practical tasks. The research also revealed ‘misconceptions’ among students about scientific methodology.

An even more recent version of what constitutes procedural knowledge is offered by the draft framework for the PISA 2015 science assessment (OECD, 2012) where procedural knowledge is defined as a knowledge of:

- Concepts of measurement e.g., quantitative [measurements], qualitative [observations], the use of a scale, categorical and continuous variables;
- Ways of assessing and minimising uncertainty such as repeating and averaging measurements;
- Mechanisms to ensure the replicability (closeness of agreement between repeated measures of the same quantity) and accuracy of data (the closeness of agreement between a measured quantity and a true value of the measure);
- The concepts of variables;
- Common ways of abstracting and representing data using tables, graphs and charts and their appropriate use;
- The control of variables strategy and its role experimental design, randomized controlled trials in avoiding confounded findings and identifying possible causal mechanisms;
- The nature of an appropriate design for a given scientific questions e.g., experimental, field based or pattern seeking.

Whilst, such knowledge does answer the questions of how scientists produce data that can be trusted it does not answer the question of answer the question of 'knowing why' such procedures are necessary. For that epistemic knowledge is necessary.

Epistemic Knowledge

Experimentation is not just a matter of knowing *how* to get reliable data—which is a procedural issue—but also *why* reliability and validity are important—which is an epistemic issue. Over the past two decades science educators have been wrestling with how to incorporate epistemic knowledge in the curriculum. The movement to address the nature of science specifically (Lederman, 1992, 2007; Matthews, 1989) can be seen as one attempt to incorporate 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*. The latest attempt can be seen in the PISA assessment framework for science in 2015 (OECD, 2012). Here epistemic knowledge is presented as an explicit feature 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 proposed constructs and defining features of science 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;
- 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—a knowledge of their role in justifying the knowledge produced by science—are a knowledge of:

- How scientific claims are supported by data and reasoning in science;
- The function of different forms of empirical enquiry 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;
- 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.

While such a list can only ever be partial and open to debate, it performs the important function of identifying and pointing towards specific aspects of knowledge that should be an outcome of asking students to engage in scientific practice.

Pedagogical Content Knowledge

The challenge for teacher educators is that the education in science that most prospective teachers have received has done little to develop an explicit knowledge of the practices in the framework or the associated procedural and epistemic knowledge. Moreover, while content knowledge is a necessary condition for good teaching it is not a sufficient condition. The very rigorous and detailed studies conducted by Kunter et al. (2013) point clearly to the importance of pedagogical content knowledge (PCK). Drawing on the work of various authors (Kind, 2009; Kunter et al., 2013; Magnusson, Krajcik, & Borko, 1999; Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013; van Driel, Verloop, & de Vos, 1998) PCK can be seen as:

- Knowledge of the potential of specific tasks for learning, their goals and purposes, their cognitive demands and the prior knowledge they require, their effective orchestration in the classroom, and the long-term sequencing required to learn the procedural and epistemic features of science.
- Knowledge of common student misconceptions and how they effect student outcomes. Prior knowledge is important as a lens for interpreting, typical errors, and ways of assessing student knowledge and comprehension
- Knowledge of a repertoire of explanations for the major ideas of science, their inherent complexity, and ways of illuminating the disciplinary nature of science.

Given that many of the aspects of the practices and how to incorporate them into the teaching of science will be unfamiliar, there is a body of PCK knowledge associated with the practices that needs to be taught. Given the time constraints and all the other bodies of knowledge that are required for teaching, how can these possibly be added to any course of initial teacher training? The answer lies not in attempting to lay out some course that teaches all of these elements but rather in remembering that most teacher certification courses must be seen as part of a continuum. Their function is to lay the foundations not to build the whole edifice. Building the edifice will require continuous professional development and lifelong learning. However, the duty of the teacher educator is to ensure that the foundations are sound and that the future teacher is aware of what forms of knowledge are required for teaching and their function. Essentially that the goal of asking students to engage in practices is not only to develop an understanding of the disciplinary core ideas but also a procedural and epistemic understanding.

Applying the principles of backwards design (Wiggins & McTighe, 2004) to our own work, the question that must be asked is what kind of performance might we reasonably expect of a student teacher by the end of a 1 year certification in this course? The broad generality of the consensus-based heuristics about the nature of science provide little guidance. Rather we might reasonably expect students to be familiar with the 8 practices that are a prominent in the NGSS. We would expect them to be able to identify some or all of the affordances that any task might offer to engage in one or more of these practices. We would also expect them to be able to point to what are the generic features of the discipline that the task and its associated practices exemplify, and some of the specific elements of content, procedural and epistemic knowledge that might be the learning outcomes of such a task. Students should also be able to identify the cognitive challenges of such task and have some sense of the common difficulties that students demonstrate. They should also be able to suggest ways in which student knowledge and understanding could be diagnosed.

Doing this requires us to be reflexive of our own practice. What kind of knowledge and understanding do we ourselves hold of the nature of science and the role of the practices embodied in NGSS? Are we cognizant of a range of tasks that might exemplify one or more of the science practices and how they illuminate features of content, procedural and epistemic knowledge. If we are to build our students' capacities to construct explanations, analyze and interpret data, develop models and engage in argument from evidence then it is necessary for teacher educator to have some plan of the structure they hope to build and its constituent elements. Otherwise practice without clear, well-specified goals is blind whilst broad goals without details provide little guidance for how they should be exemplified in the classroom. The goal of this paper has been to provide some sense of the structure and thinking that underpins the turn to practices in the NGSS. If we are to take our students in a new direction it helps to know not only where we are going but also why we are going there too.

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