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Learning science and the nature of science in three-part harmony

Richard Duschl[1]

College of Education, Penn State University

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Planning and carrying out investigations: an entry to learning and to teacher professional development around NGSS science and engineering practices

Richard A Duschl[1*] and Rodger W Bybee[2]

Abstract

The shift from science inquiry to science practices as recommended in the US reports *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* and the *Next Generation Science Standards* has implications for classroom/school level instruction and assessment practices and, therefore, for teacher's professional development. We explore some of these implications and the nuances of adopting a practice orientation for science education through the lens of one NGSS practice 'Planning and Carrying Out Investigations' (PCOI). We argue that a focus on any one practice must necessarily consider embracing a 'suite of practices' approach to guide in the design of the curriculum, instruction, assessment, and evaluation. We introduce the 5D model as a curriculum and instruction framework (1) to examine how unpacking PCOI can help teachers bridge to other less-familiar-to-teachers NGSS practices and (2) to help capture the 'struggle' of doing science by problematizing and unpacking for students the 5D component elements of measurement and observation.

1. Deciding what and how to measure, observe, and sample;
2. Developing or selecting procedures/tools to measure and collect data;
3. Documenting and systematically recording results and observations;
4. Devising representations for structuring data and patterns of observations; and
5. Determining if (1) the data are good (valid and reliable) and can be used as evidence, (2) additional or new data are needed, or (3) a new investigation design or set of measurements are needed.

Our hypothesis is that the 5D model provides struggle type experiences for students to acquire not only conceptual, procedural and epistemic knowledge but also to attain desired 'knowledge problematic' images of the nature of science. Additionally, we further contend that PCOI is a more familiar professional development context for teachers wherein the 5D approach can help bridge the gap between the less familiar and the more complex practices such as building and refining models and explanations.

Background

For scientists and engineers, PCOI has many steps involving numerous decisions and frequently requiring repeated attempts. It takes time to sort things out in the natural world, to ask the right questions, and to make the appropriate measurements and observations. The *Framework* (NRC 2012) points out, however, that such sense-making enactments are missing in our current K-12 science programs. Currently, we find in many science programs, online websites, and curriculum materials streamlined 'cookbook' investigations and out-of-date activities for K-12 students. Such cookbook and dated investigations tend to strip out the sense-making complexities of doing science and thereby omit the practices and using knowledge orientation of the *NGSS* (NGSS Lead States, 2013). If students only

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* Correspondence: rad19@psu.edu
[1]College of Education, Penn State University, University Park, PA 16802, USA
Full list of author information is available at the end of the article

encounter preplanned confirmatory investigations following step-by-step procedures that ensure the desired outcome occurs, then important and relevant thinking and designing practices and struggles that are part of doing science and engineering get stripped away. When the struggle of doing science is eliminated or simplified, learners get the wrong perceptions of what is involved when obtaining scientific knowledge and evidence. Thus, a principal goal of the *Framework* (NRC 2012) is to ensure learners' experiences with doing science emphasizes practices and reflects a bit of the struggle.

The *Framework* (2012) "stresses the importance of developing students' knowledge of how science and engineering achieve their ends while also strengthening their competency with related practices." (p 41) so as to "help students become more critical consumers of scientific information." (p 41). Engaging in investigations that are designed for making choices and decisions during planning and implementation, provides students opportunities for finding what works out and what does not. Setting up groups so that students use different ways of measuring, recording, and/or representing creates 'coming together making sense' opportunities in a classroom for sharing and comparing. Each group then presents on how they tackled the investigation. Such sharing often leads to refinements to the investigation plans, alterations in how to take measurements or perhaps a decision to start over. These are important 'doing science' experiences that develop students' insights into the nature of science and the dynamics of how scientific knowledge is generated, refined, and justified.

We hypothesize that a reconsideration of planning and carrying out investigations (PCOI) as a suite of component practices to be unpacked will help reveal to students the scientific struggles involved with building knowledge about the natural world. This upacking position is different from the 'fused practices' stance, outlined in the next section, which combines several science and engineering practice. Unpacking the suite of practices embedded in PCOI will aide and challenge teachers, too, as they engage in the monitoring and mediation of students reasoning and knowledge building. Through measurements and observations of the material world and of the designed world, scientists as well as students test claims, questions, conjectures, hypotheses and models; e.g., about nature, life on Earth, and the material composition and structure of matter and energy. Good science and engineering investigations put theories, explanations, designs and solutions to sever tests. Such sever tests are the goal of planning and carrying out investigations. Wellington and Osborne (2001) argue though that a major shortcoming of our educational programs is that we offer little to justify the current lack of focus on how science builds and refines theories, models, and explanations; e.g., epistemic practices in classrooms. Osborne and Wellington are speaking to the misplaced priorities we find in most science curriculum. That is, the persistent and dominant focus on teaching what we know. How we come to know and why we believe what we know are marginalized aspects of science learning. The long-term effect, discussed in the next section, leads to learners' acquiring incorrect images of science.

A critical step forward for changing this 'what we know' condition is engaging learners in doing science and examining the relationships between evidence and explanation. In classrooms, such opportunities typically occur when planning and carrying out investigations (PCOI) that are designed to engage learners in the nuanced decision making steps of moving from questions, to measures, to data, to evidence, and to explanation. PCOI is a complex process and frequently an iterative one, too. It takes time when designing and implementing investigations to sort things out about measuring and structuring data. If students and teachers only encounter preplanned confirmatory investigations based on tried and true step-by-step procedures always ensuring the anticipated outcome(s), then an undesirable outcome for students is that important and relevant cognitive and materials struggles of doing science get stripped away. A negative outcome for teachers is that important formative assessment and feedback-on-learning opportunities get omitted, too.

The learning sciences literature (Sawyer, 2014) informs us that the structure of knowledge and the processes of knowing and learning are much more nuanced. That is, context and content matter. We now understand how cognitive, social, and cultural dynamics of learning are mutually supportive of one another and intertwined. "[Y]ou cannot strip learning of its content, nor study it in a 'neutral' context. It is always situated, always related to some ongoing enterprise" (Bruner, 2004; p20). Thus, learning goals are not just knowing about things but also using knowledge to build and refine claims. In the STEM disciplines, knowledge use is situated in or coupled to disciplinary practices that focus on building and refining designs, solutions, models and theories.

When we synthesize the learning sciences research (c.f., Duschl, 2008) we learn:

(1) The incorporation and assessment of science learning in educational contexts should focus on three integrated domains:
    - The conceptual structures and cognitive processes used when reasoning scientifically,
    - The epistemic frameworks used when developing and evaluating scientific knowledge, and,
    - The social processes and contexts that shape how knowledge is communicated, represented, argued and debated.

(2) The conditions for science learning and assessment improve through the establishment of:

- Learning environments that promote active productive student learning,
- Instructional sequences that promote integrating science learning across each of the 3 domains in (1),
- Activities and tasks that make students' thinking visible in each of the 3 domains in (1), and
- Teacher designed assessment practices that monitor learning and provide feedback on thinking and learning in each of the three domains.

This learning sciences research focus has contributed to new views about how to engage students in school science. The *Taking Science To School* (NRC, 2007) report interprets the learning science perspectives by stating science education in grades K-8 needs to emphasize three practices:

1. Building and refining theories and models,
2. Constructing arguments and explanations,
3. Using specialized ways of talking, writing and representing phenomena.

However, if we are going to raise the learning performance bar for students, then there are implications for teachers as well. The orientation to coupling the learning of content with engagement with practices (i.e., using knowledge) and doing so within coherent sequences of instruction both within and across grade levels is a new challenge for STEM teachers. A promising perspective for beginning teacher education is the recommendation that the education of early career teachers should focus on a core set of pedagogical routines.

> A core challenge for all teacher preparation programs is to identify the knowledge and skills that are both essential for new teachers and within teachers' reach. These skills should be defined broadly enough to fit with different instructional approaches that are commonly used in teaching, readily mastered by novices, and that provide novices with a professional foundation to equip them to learn more about students and about teaching. (National Academy of Education, 2009, p 4).

These core practices and skills have come to be known as High Level or Ambitious Teaching Practices. Mark Windschitl and Jessica Thompson have a research program that is pursuing development of core practices for ambitious science teaching (Windschitl et al, 2012; Windschitl et al 2011). For them the approach is to focus on 4 discourse tools as core practices:

1. Selecting big ideas – identifying inquiry-worthy ideas
2. Eliciting students' hypotheses – attending to students' initial and unfolding ideas
3. Making sense of activity – Making meaning of science phenomena
4. Pressing for evidence-based explanation – Reasoning with explanatory models through phenomena.

Practices 3 and 4 are situated in PCOI activities. For teachers, the practices challenge is developing formative assessment routines that mediate student learning and reasoning. The 5D model suite of practices unpacks for teachers as well the critical epistemic practices that need to be monitored. Such teacher monitoring and mediation practices are labeled 'Assessment for Learning' and is distinct from evaluation practices (e.g., quizzes and tests) associated with 'Assessment of Learning' (Gitomer and Duschl, 2007). The teaching routines and assessment practices associated with PCOI lessons are indeed complex. However, as Windschitl et al (2012) argue accomplished and ambitious science teaching (i) examines and identifies the diversity of students knowledge and reasoning and (ii) mediates student learning by providing experiences and discourse opportunities that enable students to develop understandings of conceptual structures, to employ criteria for evaluating the status of knowledge claims, and to participate in communicating evidence and knowledge claims to others. Ambitious teaching involves creating classroom learning environments that promote the sharing and display of students ideas and thereby making learners' thinking visible that, in turn, make possible teachers' assessment for learning practices. The crux of the matter is simple to state but complex to implement and manage. Not unlike the 5E model, discussed in the next section, which research shows has been a very effective instructional framework for science teachers to coordinate inquiry learning, the 5D suite of practices model we hypothesize will aide teachers in successful implementation of the three *Taking Science to School* practices listed above.

Knowledge problematic and the 5D component elements

The *Framework* (NRC 2012) recommends that within 3-year grade bands (e.g., K-2 3 to 5, 6 to 8, 9 to 12), students' engagements with PCOIs should increasingly lead them to broaden and deepen the complexity of investigations, both in terms of the questions and problems being posed as well as the measures and methods being employed. The *Framework's* stance is to avoid students only doing investigations that present science knowledge and scientific inquiry in ways that are viewed as non-problematic. Non-problematic in the sense that science would be seen as a straightforward path to answers and explanations where there is no struggle: ask a question, you always get the answer; make measurements, you always selected the right tool and procedure; make observations, you always obtain the correct information knowing when and where to look.

Carey and Smith (1993), Smith et al. (2000), and Smith and Wenk (2006) report research examining K-16 students' images of science and found evidence that indeed many learners do the attainment of scientific knowledge as non-problematic. Employing the same structured interview protocols, they assigned students to one of the three levels of views about images of science

> Level 1 Students view scientific knowledge as a collection of true beliefs about how to do something correctly or as basic facts. Scientific knowledge accumulates piecemeal through telling and observation which is certain and true. Students view scientific knowledge as unproblematic.
> Level 2 Students view science knowledge as a set of tested ideas. Notions of explanation and testing hypotheses appear at this level. Here, students view science as figuring out how and why things work and absolute knowledge comes about through diligence and effort. Level 2 is a transitional level.
> Level 3 Students see scientific knowledge consisting of well-tested theories and models that are used to explain and predict natural events. Theories are seen as guiding inquiry and evidence from experiments is not only used for/against hypotheses but theories as well. Theories and models are also seen as more or less useful rather than strictly right or wrong, and that knowledge of world is fundamentally elusive and uncertain. Students view scientific knowledge as problematic.

Carey et al. (1989) asked seventh graders a series of questions about the goals and practices of science and about the relationships between scientists' ideas, experiments, and data. Here, too, they found the same global perspectives about the nature of science.

- Level 1 in which scientists were regarded simply as collecting facts about the world: knowledge unproblematic
- Level 2 transitional
- Level 3 in which scientists were seen as concerned with building ever more powerful and explanatorily adequate theories about the world: knowledge problematic

Another interview study (Grosslight et al. 1991) probed middle school students' understanding of models and modeling and achieved similar results.

- Level 1 Many children regarded models merely as copies of the world.
- Level 2 Children understood that models involve both the selection and omission of features, but emphasis remained on the models themselves rather than on the scientists' ideas behind the model.
- Level 3 Models were regarded as tools developed for the purpose of testing theories.

Driver et al. (1996) report similar results. Researching students' images of science, they found that students who complete too many investigations, year in and year out, that are designed to follow a set of procedures thus ensuring sound results, fail to recognize that the results of investigations are used in science to engage in model building and revision activities. In other words, the impression students acquire is that science investigations typically work and the anticipated outcomes are usually achieved. Absent are the struggles that scientists encounter when trying to decide how, what, where, and when to measure or observe what some researchers (Lehrer et al. 2008; Ford, 2008; Duschl, 2008) refer to as 'getting a grip on nature.' A steady diet of such investigations-without-struggles seems to lead students to leave school with the level 1 naïve notions: obtaining results from investigations and developing scientific knowledge are non-problematic.

A National Research Council study, *America's Lab Report* (NRC, 2006), provides a possible explanation for the results described in the aforementioned studies. The study found that the sequence of instruction and role of laboratory activities often are experienced as separate. The NRC report recommended greater use of integrated instructional units.

Integrated instructional units have two key features. First, laboratory experiences and other educational experiences are carefully designed to help students attain learning goals. Second, the laboratory experience is explicitly connected to and integrated with other learning experiences. Our proposal of a 5D framework is intended to address the need for an integrated instructional approach to Planning and Carrying Out Investigations.

PCOI can instead reveal how obtaining, building, and refining scientific knowledge through scientific inquiries involves working through a variety of complexities or what we introduce in the 5D framework as a suite of practices embedded in five component elements of measurement and observation. Our position is that a focus on any one practice must necessarily embrace a suite of practices approach to guide in the design of curriculum, instruction, assessment, and evaluation. Songer has advanced the notion of 'fused' practices as a strategy for bundling together *NGSS* core ideas, crosscutting concepts, and science and engineering practices. In Songer et al. (2009) and Gotwals and Songer (2013), the core idea *biodiversity* is blended with the crosscutting concept *patterns* and three fused practices: *planning and carrying out investigations, analyzing and interpreting data, and constructing explanations*. Rather than bundling practices, we advocate a practice unpacking stance. The 5D model takes up a suite of practices orientation that captures the struggle of doing science by problematizing and unpacking component PCOI elements of measurement and observation. Once problems have been posed, questions asked, or hypotheses stated, scientists and engineers turn to a set of component elements that typically include the following:

1. Deciding what and how to measure, observe, and sample;
2. Developing or selecting procedures/tools to measure and collect data;
3. Documenting and systematically recording results and observations;
4. Devising representations for structuring data and patterns of observations; and
5. Determining if (1) the data are good (valid and reliable) and can be used as evidence, (2) additional or new data are needed, or (3) a new investigation design or set of measurements are needed.

Our hypothesis is that the component elements deciding, developing, documenting, devising, and determining in the 5D provides struggle type experiences for students that will lead (1) to acquiring conceptual, procedural, and epistemic knowledge and (2) to attaining desired knowledge problematic images of the nature of science.

The proposed 5D model has general connections to the BSCS 5E Instructional Model (Bybee, 2015). The 5D model is specific to the challenge of Planning and Conducting Investigations while the BSCS 5E model has wider or more general applicability. Beyond the parallel of the two models, we also note research supporting the positive learning outcomes and use of the 5E model (Scott et al., 2014; Wilson et al., 2010; Taylor et al., 2015).

Discussion

Complexities in school science investigations

Taking Science to School (NRC, 2007), the synthesis study report of K-8 science learning, takes up the review of PCOI issues in chapter 5 - 'Generating and Evaluating Scientific Evidence and Explanations.' It is beyond the scope of the article to present a full synthesis of the research from chapter 5. However, a reading of the chapter's section and subsection headings offers up important insights about the landscape of school science investigations that teachers will need to become proficient:

- Generating Evidence
    - ○ Asking questions and formulating hypotheses
    - ○ Designing experiments
    - ○ Observing and recording
- Evaluating Evidence
    - ○ Co-variation evidence
    - ○ Evidence in the contexts of investigations
- Beliefs about causal mechanisms and plausibility
- Evaluating evidence that contradicts prior beliefs
- The importance of experience and instruction
- Representational systems that support modeling
    - ○ Mathematics
    - ○ Data
    - ○ Scale models, diagrams, and maps

In order to get a better sense of the complexities that exist in PCOI, consider the two general statements in the *Framework* (2012; p 50) that distinguish science and engineering investigations. The general goal is designing experiences where students are using prior knowledge and evidence to build and refine models, designs, and explanations.

Scientific investigation may be conducted in the field or the laboratory. A major practice of scientists is planning and carrying out a systematic investigation, which requires the identification of what is to be recorded and, if applicable, what are to be treated as the dependent and independent variables (control of variables). Observations and data collected from such work are used to test existing theories and explanations or to revise and develop new ones.

Engineers use investigation both to gain data essential for specifying design criteria or parameters and to test their designs. Like scientists, engineers must identify relevant variables, decide how they will be measured, and collect data for analysis. Their investigations help them to identify how effective, efficient, and durable their designs may be under a range of conditions.

In classrooms and out-of-school learning environments that engage learners in conducting experiments and investigations, there exist some general distinctions for PCOI. One important distinction brought out in the 'Designing Experiments' section that reviews the literature on children designing experiments is the differences between knowledge lean and knowledge rich activities. Domain-general experiments and demonstrations typically stress the learning of a strategy (e.g., control of variables) in simplified stripped down conceptual knowledge contexts. The experiments and investigations are typically completed in one or two lesson periods and minimize the need to consider relevant domain-specific prior knowledge. Thus, the design of domain-general investigations is viewed as having knowledge lean requirements. An example is doing a control of variable (COV) experiment to find the law of the pendulum. The experimenter isolates three variables (length of string, size of weight, height from which weight is released) to determine which variable(s) influences the period/time of swing. In this case, only the length of the string changes the period of the pendulum.

Engaging learners in the design of domain-specific experiments/investigations that are knowledge rich and less constrained reveal very different patterns of engagement by children. Such experiences typically require a sequence of lessons over days and perhaps weeks to complete and, importantly, also require the use of prior knowledge. An example, building on the domain general COV activity, is posing a challenge to students to construct a pendulum that can be used as 1 s/period counter or second timer. Here, time measurements from an array of different length pendulums are used to develop a data set. The data set, in turn, is used to build a data structure representation to find which pendulum length has a 1-s period. Extensions of the lesson could predict and then investigate if different materials (e.g., wooden dowels, metal pipes, and chains) as the same length of the string would produce a 1-s swinger/pendulum. Domain-specific investigation researches were found to have knowledge rich requirements and demands.

Another important distinction for PCOI is adopting a learning progression or perspective for engaging in PCOI. The *NGSS Science and Engineering Practices Grade Band Matrix* suggests the following 'end of grade band goal statements' that appear in the PCOI:

- Investigations based on fair tests to support explanations or design solutions (K-2).
- Investigations that control variables and provide evidence to support explanations or design solutions (3 to 5).
- Investigations that use multiple variables and provide evidence to support explanations or design solutions (6 to 8).
- Investigations that build, test, and revise conceptual, mathematical, physical, and empirical models (9 to 12).

The 5D model component elements deciding, developing, documenting, devising, and determining frame the kind and type of problematic processes that the students of K-12 might consider or encounter when engaging in PCOI activities. The intent is to allow such PCOI experiences to unfold and enable rich opportunities for discussions and engagements to take place. The basic idea is to problematize the data and evidence generated in an investigation and get students to represent and talk about the data and evidence. Hence, the recommendation we are making with the 5D model is to unpack PCOI in terms of problems of measurement and measuring. What measurements should be taken? What is the sample and size of sample for taking the measures? Is the sample size sufficient and well constructed to address issues of chance outcomes? What level of accuracy and precision do you want? What instruments or tools should be used to make such measurements? Precision is very important and opens up many other problems to achieve the goal to measure and record as accurately as possible so as to try and eliminate as many sources of error as possible. Then there are the precision issues when doing field studies such as conducting observation, conducting counts, gathering samples, and generating representations and drawings. Once again, we see how obtaining, building, and refining scientific knowledge becomes problematic.

Another relevant distinction is the types of hypothesis-based investigations scientists and engineers develop. Scientists and engineers have two fundamental goals when investigating and observing the world: (1) systematically describe the world; and (2) develop and test models, mechanisms, theories, and explanations for how the world works. The three broad categories for such investigations are the following:

- Generate observations/measurements that induce a hypothesis to account for a pattern - (discovery context)
- Test existing hypotheses under consideration against one another - (confirmation/verification context)
- Isolating variables or controlling variable investigations that allow for valid inferences and also to put constraints on the number of possible experiments to consider.

Planning investigations begins with designing experimental or observational inquiries that align to the question(s) being asked or the hypothesis being put forth. One begins this process by considering the relevant properties, attributes, and variables and then determining how they may be observed, measured, isolated, or controlled. Isolating and controlling variables are important for determining patterns, establishing cause and effect relationships, and building mechanisms to explain or describe events and systems. In laboratory experiments, students need to decide the following:

- which variable(s) will be treated as results, the outcomes of the experiment that are allowed to be different and vary, and
- which variable(s) are to be treated as the inputs and thus must be held constant, that is controlled.

Another distinction is between lab and field investigations. In field observations, planning investigations are very different and begin with finding out what can and cannot be controlled and then deciding when to do measurements or how to collect different samples of data under different conditions. A model-based approach is needed. The range of choices, the complexities with obtaining and setting up materials, and the wide variety of sources of error are what makes scientific knowledge problematic - it is complex work and involves planning and thinking that can frequently be inaccurate or misdirected, yet another important aspect of the scientific struggle that makes science knowledge problematic and difficult to attain.

Forms of knowledge, ways of knowing

The *Framework* (NRC, 2012) 'stresses the importance of developing students' knowledge of how science and engineering achieve their ends while also strengthening their competency with related practices' (p 41) so as to 'help students become more critical consumers of scientific information' (p 41). Engaging in the 5D component elements for PCOI pushes students into making choices and making decisions, some that might work out and some that might not. Setting up groups so that students use different ways of measuring, recording, and/or representing creates 'coming together making sense' opportunities in a classroom (Duschl, 2003). A teacher can ask at the end of the lessons, 'So, what did we find out, what did we learn about the design and procedures of the investigation?' Each group then presents on how they tackled the investigation. Such sharing often leads to refinements to the investigation plans, alterations in how to take measurements, or perhaps a decision to start over (Duschl and Gitomer 1997). These are important 'doing science' experiences that develop students' insights into the workings of science and understandings of how scientific knowledge is generated and justified.

Engaging students in coming together events for considering, reviewing, and critiquing the design of experiments and investigations, the data gathering and measurement plans, and the quality of data and evidence obtained are important conversations to have before, during, and/or after carrying out investigations (Engels & Contant, 2002). As stated in the *Framework,* (NRC, 2012) '[u] understanding how science functions requires a synthesis of content knowledge, procedural knowledge, and epistemic knowledge' (p 78). Both procedural and epistemic knowledge are strongly located in PCOI.

Procedural knowledge as used in the *Framework* (NRC, 2012) represents the suite of methods scientists and engineers use to ensure findings are valid and reliable. Again, scientists and engineers make many decisions to ensure that data are accurate and that the evidence obtained is valid (true measures or observations) and reliable (obtained using procedures that can be repeated). Procedures such as using control groups to test the effect of treatments, sampling procedures to make sure what you are measuring/observing is representative of the larger population, double-blind studies to eliminate any chance of bias, and establishing the precision of measurement are examples of how scientists go about studying nature.

Epistemic knowledge is knowledge of the various sets of criteria, rules, and values held in the sciences and in engineering disciplines for deciding 'what counts' or 'what is best.' Examples of epistemic knowledge include deciding what is a fair test, a precise and accurate measurement, systematic observations, testable hypotheses, etc. Epistemic knowledge is more often than not developed and decided by communities and not by individuals. Scientists and engineers develop epistemic knowledge when writing papers or presenting to research groups and at conferences. The goal is being able to explain how we have come to know what we know and why we believe this explanation over alternatives. Each of the 5Ds can be seen as a knowledge-building component of PCOI and thus constitutes epistemic knowledge.

Considering the 5D components presented above, PCOI lesson sequences may stress one or more of these elements. Engaging students with inventing measures or selecting measures from a set of options opens up important dynamics about the nature of scientific inquiry. So, does allowing students to invent representations or choose among options for graphically presenting results enhance scientific inquiry learning experiences? (Lehrer and Schauble, 2000, 2002).

Our position is that unpacking the component elements for students is a critically important goal for instruction over the course of the school year as well as over a grade band (e.g., K-2 3 to 5, 6 to 8, 9 to 12), and we would maintain that the unpacking of PCOI is also a viable and powerful initial context for designing K-12 NGSS teacher professional development programs addressing the instructional coordination of the Frameworks 3 Dimensions. Even more so, it provides students with 'doing' opportunities with these component practice elements. It is worthwhile then to consider the long-term end of K-12 goals the *Framework* puts forth for the third S and E practice - planning and carrying out investigations.

By grade 12, students should be able to do the following:

- Formulate a question that can be investigated within the scope of the classroom, school laboratory, or field with available resources and, when appropriate, frame a hypothesis (that is, a possible explanation that predicts a particular and stable outcome) based on a model or theory.
- Decide what data are to be gathered, what tools are needed to do the gathering, and how measurements will be recorded.
- Decide how much data are needed to produce reliable measurements and consider any limitations on the precision of the data.

- Plan experimental or field-research procedures, identifying relevant independent and dependent variables and, when appropriate, the need for controls.
- Consider possible confounding variables or effects and ensure that the investigation's design has controlled for them.

Conclusions

The *Framework* (NRC, 2012) rightfully stresses that the science and engineering practices should begin in the very earliest grades and then progress through middle school to high school engaging students in ever more complex sophisticated levels of performances. Here, we have focused on unpacking PCOI to demonstrate how an emphasis on measurement and observation using the 5D framework invokes a suite of practices that occur when designing and conducting such inquiries. We have discussed the importance of opportunities to design investigations so students can learn the importance of decisions surrounding what and when to measure, how and where to sample or observe, what to keep constant, and how to select or construct data collection tools and instruments that are appropriate to the needs of an inquiry. Students also need experiences that are outside the laboratory so they learn it is not the sole domain for scientific inquiry. For many scientists (e.g., geographers, geologists, oceanographers, field biologists, psychologists, ecologists), the 'laboratory' is the natural world where experiments are conducted and data are collected in the field. In the elementary years, students' experiences should be structured to help them learn to plan investigations and define the features to be investigated such as looking for patterns and interactions that suggest causal relationships. 'From the earliest grades, students should have opportunities to carry out careful and systematic investigations, with appropriately supported prior experiences that develop their ability to observe and measure and to record data using appropriate tools and instruments' (NRC, 2012, p 60-61).

At all grade levels, there is a need for balance between investigations structured by the teacher and those that emerge from students' own questions or from authentic investigations of agreed upon problems; e.g., the source of a classroom's fruit flies (Lehrer and Schabule, 2002). Students should have several opportunities to engage in practices where they decide what data are to be gathered, what variables should be controlled, and what tools or instruments are needed to gather and to record data with precision. Recall, that a *Framework* goal is to avoid students developing 'knowledge unproblematic' views of science knowledge and scientific inquiry. Planning and carrying out investigations employing the 5D unpacked practices are important experiences that help students engage with conceptual knowledge, procedural knowledge, and epistemic knowledge and encounter struggle experiences that can help develop a knowledge problematic view of scientific inquiry.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The authors have contributed equally to the manuscript. Both authors read and approved the final manuscript.

Author details

[1]College of Education, Penn State University, University Park, PA 16802, USA.
[2]BSCS, Golden, CO 80401, USA.

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Naturalizing the Nature of Science - Melding Mechanisms, Models, and Minds

Richard A. Duschl
The Pennsylvania State University, USA

The evolving relationship between epistemology and cognitive science during the 20th century has led to the emergence of the naturalized view philosophy of science. The trajectory of philosophy of science during the latter half of the 20th century was away from a formal orientation toward a naturalized philosophy grounded in history and psychology. This presentation focuses on two complementary developments: 1) the mid-20th century historical turn advancing the image of science as grounded in theory-building/refining practices building to 2) the contemporary cognitive turn image of science as grounded in mechanism and modeling practices. The 7 Tenets of the Nature of Science will be presented as framework for examining the transition from the 'Traditional NOS' view of logicial positivism to the 'Naturalized' view of NOS. One conclusion is that neither the extreme positivistic (ignoring psychology) nor sociology of knowledge (ignoring epistemology) positions are viable for advancing effective models of science education.

As science studies have moved beyond physics to include chemistry, earth science and biology the important role of models in those disciplines has risen, perhaps even to the extent of largely displacing theories as the central organizing concepts. Studies of the structure of disciplines have shifted from the physical sciences to the systems-based Life and Earth/Environmental sciences. Science studies commitments to causal reduction-based analyses are being challenged by emergence-based complexity analyses of science. A fundamental consideration is the influential role investigative and communicative tools and technologies (e.g., the historical material and social environment of science) have on studying complexity and on the growth of knowledge. My position is that methodological changes in scientific practices are an important but oft ignored dynamic in conceptual change theory driven images of science and science education. New measurements and new evidence have driven the formulation of scientific practices and explanatory models and mechanisms. The implication for science education is that didactical models for teaching sequences and learning progressions need to consider the central role contemporary epistemological and psychological frameworks have in guiding the design of science learning environments.

NOS and Science Education

When and how did images about the nature of science become a targeted curriculum topic and a focused learning goal in K-16 science education? From a US perspective, the decade of interest is the 1950s. In that decade, post-war developments in science education shifted from industry efforts (e.g., General

Electric, Westinghouse) to broader federal agendas with the formation of the National Science Foundation. Then, as now, the focus was on developing a competitive workforce to drive the economy but importantly it was also to win the 'cold war.'

The catalyst for rapidly changing the face of K-12 science education in the 1950s was the US reaction to the launching of the USSR satellite Sputnik. Within one decade, 1955 to 1965, hundreds of millions of dollars were invested in the development of curriculum and facilities, employing a top-down high school first followed by middle grades and elementary grades set of processes. Once the curricula were established, NSF funding was then directed to teacher institutes to prepare staff to teach these new inquiry-based science programs. Scholarly writings on this period of science education can be found in books by John Rudolph's *Scientists in the Classroom*, George DeBore's *The History of Science Education,* and my own *Restructuring Science Education: The Role of Theories and their Importance.*

The catalyst in post-secondary education was Harvard University and President James Conant's project to make science education for returning WWII GIs based on historical cases studies of select scientific episodes (e.g., Boyle's Laws, Newton's Laws, among others). In the 1950s and 1960s, Harvard University was the center of activity in history of science (HOS) and of the application of HOS to science education. Scholarly luminaries such as I.B. Cohen, Thomas Kuhn, Gerald Holton, Stephen Brush, James Rutherford, Fletcher Watson, Leo Klopfer and Glen Aikenhead, among others, were at Harvard. Development of the *Harvard Cases in History of Science* undergraduate curriculum involved none other that Thomas Kuhn who while working on cases in physics (e.g., Newton's Laws) began to build his ideas that led to his seminal publication – *The Structure of Scientific Revolutions.* Also emerging from this caldron of scholarly activity was the NSF-funded *Harvard Project Physics* that fused HOS into a high school physics course.

Conant's *On Understanding Science* and other of his policy books on the structure of secondary education led to the development of ideas, and subsequently practices, regarding the comprehensive high school and the importance of science and mathematics as core subjects. Scholarly writings on this period of Kuhnian historically minded philosophy of science and science education include Kuhn's *Structures* itself, the *Road to Structures* edited by Conant's grandson Jim Conant (200?) and Steve Fuller's (200x) [title of book], a social epistemological deconstruction of Kuhn's time at Harvard.

Concomitant with curriculum development activities that made HOS and the nature of science (NOS) a topic of study were developments of measurements that began the processes of making NOS a learning goal. Once again, the process begins with Harvard based scholars. Cooley and Klopfer (1964) develop the 'Test of Understanding Science' and Welch and Aikenhead (19xx) the attitudes measure. Over the next 3 decades a wide variety of instruments were developed to assess students' understandings of and attitudes toward science as a way of knowing.

Consider the 40-year evolution of NSTA Position Statements on Nature of Science, Nature of Inquiry and Images of Child Development as changes in theories of learning, images of science, and images of inquiry took hold.

In the US, the watershed event was the publication of the AAAS Benchmarks of Science Education and of the NRC National Standards in Science Education. Each but in very different ways incorporates HOS and NOS into their frameworks for the design of State science standards. Thus, reinforcing the need for measures of learning to guide learning and instruction and thereby fixing views about the nature of science and the nature of inquiry. Different research groups conducted thoughtful and thorough scholarship. A feature or common denominator of this research was establishing a set of topics, themes, or views that would inform and guide the assessment of student learning and the design of curriculum.

Demarcation and the Path to Naturalized Philosophy of Science

The parade of science over the last 300 years has been dynamic, to say the least. New tools, technologies and theories have shaped science pathways first in physics and chemistry for the early paradigmatic sciences; in population biology through Darwinian Evolution, the Great Synthesis and on to molecular biology and medical sciences; in quantum mechanics; in material, communication and information sciences; in geosciences and Earth systems sciences; in neurosciences and brain sciences, to name but a few. Advancements in science over the centuries have spawned multiple philosophical perspectives to account for the thinking and growth of knowledge therein. Over the last 100 years there are three major periods in philosophy of science:

1. The experiment-based hypothesis testing view that gave us Logical Positivism, Logical Empiricism and Deductive-nomological explanations to account for the justification of scientific knowledge claims.
2. The history-based view of theory development and conceptual change that gave us Paradigms, Research Programmes, Heuristic Principles, Scientific thema, and Research Traditions to account for the rational growth of scientific knowledge.
3. The model-based view of cognitive and social dynamics among communities of scholars that gave us social epistemology, naturalized philosophy of science, and accompanying epistemologies to account for the deepening and broadening of scientific explanations.

Across these three periods let me propose 6 steps that help move the conversations forward:

1. Emergence of the Social Pragmatic View of Language via accounts of the 'Causal Theory of Reference' and the failure of formal inductive syntactical structures to explain explanations.
2. Emergence of Cognitive Psychologies as the dominance of Behaviorism recedes leading to Sense Data and Theory of Mind
3. Emergence of Philosophy of Biology to introduce evolutionary ideas about emergence and the treatment of anomalous data.
4. Emergence of History of Science and the subsequent shift from accounts of older history to accounts of newer or contemporary history to establish growth of knowledge mechanisms.
5. Emergence of 'Practices' and Epistemic Cultures – cognitive and social – as a basis interpreting the building and refining of scientific knowledge and methods.
6. Complex Systems Science (Discovery Science) and emergence

Practices and Science Education

Pickering's (1990) "practical realism" or interpretation of "science as practice" offers a robust appreciation for the *complexity* of science, its "rich plurality of elements of knowledge and practice," which he has come to call the "the mangle of practice." . . . . As against the "statics of knowledge," the frame of existing theoretical ideas, Pickering (1990) situates the essence of scientific life in the "dynamics of practice," that is, "a complex process of reciprocal and interdependent tunings and refigurings of material procedures, interpretations and theories."

For Pickering, scientific inquiry during its planning and implementation stages is a patchy and fragmented set of processes mobilized around resources. Planning is the contingent and creative designation of goals. Implementation for Pickering (1989) has

> "three elements: a "material procedure" which involves setting up, running and monitoring an apparatus; an "instrumental model," which conceives how the apparatus should function; and a "phenomenal model," which "endows experimental findings within meaning and significance . . . a conceptual understanding of whatever aspect of the phenomenal world is under investigation. The "hard work" of science comes in trying to make all these work together" (Zammito, 2004; pp. 226-227).

Explicit Instruction – Heuristic Principles vs. E-E Continuum

Since the 1950s the evolution of thought regarding the nature of science has progressed through 3 changing images of science:

- *science as hypothesis testing,*
- *science as theory change*
- *science as model building and revising*

The contemporary understanding of the nature of science holds that the majority of scientists' engagement is not individual efforts toward final theory acceptance, but communities of scientists striving for theory improvement and refinement. What occurs in science is not predominantly the context of discovery or the context of justification but the contexts of theory development, of conceptual modification. Thagard (2007) posits that explanatory coherence of scientific explanations is achieved through the complementary process in which theories broaden and deepen over time by accounting for new facts and providing explanations of why the theory works.

Developing epistemic criteria and evaluating the epistemic status of ideas are viewed as necessary elements in a conceptual ecology of science learning environments that seek to promote enculturation into scientific cultures and/or achieve NOS learning goals. The recommended shifts are:

(1) Away from a focus on the individual scientist to a focus on social groups or communities of scientists;

(2) Away from a foci on contexts of discovery and justification of conceptual claims to a foci on the development, modification and evolution of epistemic claims; and

(3) Away from an exclusive focus on inquiry addressing the fit of concepts in scientific theories to a focus on the tools and technologies that give rise to new methods and practices in building and refining scientific models.

(4) Away from domain-general 'consensus view lists of NOS' to views of NOS that are situated practices associated with the broadening and deepening of the growth of scientific knowledge.

Recent research reviews of (Duschl, 2008; Duschl & Grandy, 2008; Ford & Forman, 2006; Lehrer & Schauble, 2006) and research studies on science learning (Ford, 2008; Lehrer, Schauble, & Lucas, 2008; Smith, Wiser, Anderson & Krajcik, 2006) maintain that the similar broadening and deepening practices ought to hold in science learning environments. The NRC (2007) research review on K-8 science learning recommends organizing science education – curriculum-instruction-assessment - around three important broadening and deepening epistemic and social practices:

1. Building theories and models,
2. Constructing arguments.
3. Using specialized ways of talking, writing and representing natural phenomena.

Revising Views about the Nature of Science

Developments in scientific theory coupled with concomitant advances in material sciences, engineering and technologies have given rise to radically new ways of observing nature and engaging with phenomenon. At the beginning of the 20th century scientists were debating the existence of atoms and genes, by the end of the century they were manipulating individual atoms and engaging in genetic engineering. These developments have altered the nature of scientific inquiry and greatly complicated our images of what it means to engage in scientific inquiry and conceptual change. Where once scientific inquiry was principally the domain of unaided sense perception, today scientific inquiry is guided by highly theoretical beliefs that determine the very existence of observational events (e.g., neutrino capture experiments in the ice fields of Antarctica).

One of the important findings from the science studies literature is that not only does scientific knowledge change over time, but so, too, do the methods of inquiry and the criteria for the evaluation of knowledge change. The accretion growth model of scientific knowledge is no longer tenable. Nor is a model of the growth of knowledge that appeals to changes in theory commitments alone; e.g., conceptual change models. Changes in research programs that drive the growth of scientific knowledge also can be due to changes in methodological commitments or goal commitments (Duschl & Grandy, 2008). Science studies examining contemporary science practices recognize that both the conceptual frameworks and the methodological practices of science have changed over time. Changes in methodology are a consequence of new tools, new technologies and new explanatory models and theories that, in turn, have shaped and will continue to shape scientific knowledge and scientific practices.

The dialogical processes of theory development and of dealing with anomalous data occupy a great deal of scientists' time and energy. The logical positivist's “context of justification” is a formal final point--the end of a journey; moreover, it is a destination few theories ever achieve, and so over emphasis on it entirely misses the importance of the journey. Importantly, the journey involved in the growth of scientific knowledge reveals the ways in which scientists respond to new data, to new theories that interpret data, or to both. Thagard’s (2007) eloquently elaborates on the dynamics of these practices as they relate to achieving explanatory coherence. Advancing explanatory coherence, he argues, involves theories that deepen and broaden overtime by respectively accounting for new facts and providing explanations through accounts of mechanisms of why the theory works.

In very broad brushstrokes, then, 20th century developments in science studies can be divided into three periods. In the first, logical positivism, with its emphasis on mathematical logic and the hypothetico-deductive method, was dominant. Logical positivism views of science held to following assumptions:

- There is an epistemologically significant distinction between observation language and theoretical language and that this distinction can be made in terms of syntax or grammar.
- Some form of inductive logic would be found that would provide a formal criterion for theory evaluation,
- There is an important dichotomy between contexts of discovery and contexts of justification.

In the 1950s and 60s, the second period, various writers questioned these and other fundamental assumptions of logical positivism and argued for the relevance of historical and psychological factors in understanding science. Thomas Kuhn introduced the conception of paradigm shifts in the original version of *Structure of Scientific Revolutions*, and then revised it in the postscript to the 1970 second edition, introducing the concept of a **disciplinary matrix**. In his disciplinary matrix view of science, theories play a central role, but they share the stage with other elements of science, including a social dimension of values and judgments. Although Kuhn saw the scientific communities as essential elements in the cognitive functioning of science, his early work did not present a detailed analysis.

The most recent movements and the third period of 20th century philosophy of science can be seen as filling in some of the gaps left by Kuhn's undoing of the basic tenets of logical positivism. This movement:

- Emphasizes the role of models and data construction in the scientific practices of theory development.
- Sees the scientific community, and not the individual scientist alone, as an essential part of the scientific process.
- Sees the cognitive scientific processes as a distributed system that includes instruments, forms of representation, and agreed upon systems for communication and argument.

7 Revised Tenets of Nature of Science

The contemporary understanding of the nature of science (NOS) is the recognition that most of the theory change that occurs in science is not final theory acceptance, but improvement and refinement of theories and models (Duschl & Grandy, 2008). What occurs in science is not predominantly the context of discovery or the context of justification as the logical positivists proposed, but the context of theory development, of conceptual modification.

The *7 revised tenets* of science proposed by Duschl and Grandy (2008) characterize how the initial received views of the logical positivism have been revised. Looking across the *7 revised tenets,* (See Appendix 1) the bold implication is the need to consider developing an enhanced notion for the scientific method. The enhanced scientific method is a view that recognizes the role of experiment and hypothesis testing but does so with a further recognition that the practices of scientific inquiry (1) have conceptual, epistemic and social dimensions and (2) are epigenetic. The expanded scientific method would be inclusive, not exclusive, of the 3 sequential images of the nature of science: Hypothetico-deductive experiment driven science; Conceptual Change theory driven science; Model-based driven science. The implication is that science as a practice has social and epistemological dynamics that are critical to engaging in the discourse and dialogical strategies that are at the core of what it means to being doing scientific inquiry.

The Revised NOS View stresses the dialogic and dialectical processes/practices of science and does so with respect to conceptual (theories and models) as well as methodological (tools and technologies) changes in scientific inquiry. The major points from the 7 Tenets are placed in an order below that reflects the improvement and refinement practices of scientific inquiry. The major points from the 7 Tenets are:

- The bulk of scientific effort is not theory discovery or theory acceptance but theory improvement and refinement.

- Research groups or disciplinary communities are the units of practice for scientific discourse.
- Scientific inquiry involves a complex set of discourse processes.
- The discourse practices of science are organized within a disciplinary matrix of shared exemplars for decisions regarding the a) values, b) instruments, c) methods, d) models, and e) evidence to adopt.
- Scientific inquiry has epistemic and social dimensions, as well as conceptual.
- Changes in scientific knowledge are not just in conceptual understandings alone; important advancements in science are also often the result of technological and methodological changes for conducting observations and measurements.
- What comes to count as an observation in science evolves with the introduction of new tools, technologies and theories.
- Theories can be understood as clusters of models where the models stand between empirical/conceptual evidence and theoretical explanations.
- Theory and model choices serve as guiding conceptions for deciding 'what counts' and are an important dynamic in scientific inquiry.
- Rubrics for a rational degree of confirmation are hopeless, dialogue over merits of alternative models and theories are essential for refining, accepting or rejecting them and are not reducible to an algorithm.

The expanded view of the NOS, then, would be inclusive, not exclusive, of the 3 sequential 20th century images of the nature of science: Hypothetico-deductive experiment driven science; Conceptual Change theory driven science; Model-based driven science. The expanded NOS view recognizes the role of experiment and hypothesis testing in scientific inquiry, but emphasizes that the results of experiments are used to advance models and build theories. Thus, the expanded NOS view makes a further recognition that the practices of science involve important dialogic and dialectical practices that function across conceptual, epistemic and social dimensions.

The implication of focusing on scientific practices involving evidence, measurement, models and use of tools and data texts is that the language and practices of science is different from normal conventions or conceptions of language. The language of science includes mathematical, stochastic, representational and epistemological elements as well as domain-specific descriptors and forms of evidence. The challenge for science education and for assessments that guide and inform learning is one of understanding how to mediate, progress and coordinate language and knowledge acquisition in these various and typically domain-specific epistemic and social practices. The problem is principally about the curriculum and how the curriculum aligns with instruction and assessment. Assessment scholars refer to this as the coherence problem – aligning classroom formative assessments with high stakes summative assessments. (Gitomer & Duschl, 2007).

Coherence – Aligning Curriculum with Assessments

Emerging theories of science learning and science practices have benefited from a much clearer articulation of the development of reasoning skills, suggesting radically different instructional and assessment practices. Instructional implications have been represented in learning progressions (e.g., Quintana et al, 2004; Smith et al. 2006) describing the development of knowledge and reasoning skills across the curriculum within particular conceptual areas, as students engage in the socio-cultural practices of science. Clarification of these progressions is critical, since current science curricular specifications and standards are seldom grounded in any understanding of the cognitive development of particular concepts or reasoning skills. These instructional sequences are responses to science curricula that have been criticized for their redundancy across years and lack of principled progression of concept and skill development (Kesidou & Roseman, 2002).

A more integrated view of science learning is expressed in the recent NRC report articulating the future of science assessment (Wilson & Bertenthal, 2005). The report argues that science assessment tasks should reflect and encourage science activity that approximates the practices of actual scientists by embracing a socio-cultural perspective and the idea of legitimate peripheral participation, in which learning is viewed as increasingly participating in the socio-cultural practices of a community. The NRC committee proposes models of assessment that engage students in sustained inquiries sharing many of the social and conceptual characteristics of what it means to "do science." Instead of disaggregating process and content, assessment designs are proposed that integrate skills and understanding to provide information about the development of both conceptual knowledge and reasoning skill.

Despite progress in science learning theory, curricular models such as learning progressions, and assessment frameworks, developing instructional practice coherent with these visions is no simple task. Coherence requires curricular choices to be made so that a relatively small number of conceptual areas are targeted for study in any given school year. If sustained inquiry is to be taken seriously, as embodied in the work on learning progressions, then large segments of the existing curricular content will need to be jettisoned. It is impossible to envision a curriculum that pursues the knowing and doing of science expressed in learning progressions while also attempting to cover the very large number of topics that are now part of most curricula (Gitomer, 2008).

The implications for large-scale assessment are profound as well. Assessing constructs such as inquiry requires going beyond the traditional content-lean approach described by Pine et al. Instead, assessing the *doing* of science requires designs that are much more tightly embedded with particular curricula. Making the difficult curricula choices that allows for an instructional and assessment focus is the only way external coherence with learning theory can be achieved.

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Appendix A

Nature of Science 7 Tenets

Traditional Tenets from Logical Positivism	***Received NOS Views***	***Reasons for Revision***	***Revised NOS Views***
1. There is an important dichotomy between contexts of discovery and contexts of justification.	*Logical positivism's focus was on the final products or outcomes of science. Of the two end points, justification of knowledge claims was the only relevant issue. How ideas, hypotheses and intuitions are initially considered or discovered was not relevant.*	*Theory change advocates value understanding the growth of knowledge begins. Perhaps the most important element Kuhn and others added is the recognition that most of the theory change is not final theory acceptance, but improvement and refinement.*	*The bulk of scientific inquiry is neither the context of discovery nor the context of justification. The dominant context is theory development and conceptual modification. The dialogical processes of theory development and of dealing with anomalous data occupy a great deal of scientists' time and energy.*
2. The individual scientist is the basic unit of analysis for understanding science.	*Logical positivists believed scientific rationality can be entirely understood in terms of choices by individual scientists.*	*Kuhn's inclusion of the scientific community as part of the scientific process introduced the idea of research groups or communities of practice as being the unit of scientific discourse. This shift from individual to group produced negative reactions*	*Scientific rationality can be understood in terms of dialogic processes taking place as knowledge claims and beliefs are posited and justified. Scientific discourse is organized within a disciplinary matrix of shared exemplars; e.g., values, instruments, methods, models,*

		from many philosophers. Including a social dimension was seen as threatening the objectivity and rationality of scientific development. Teams of scientists engage in investigations.	*evidence.*
3. There is an epistemologically significant distinction between observational and theoretical (O/T) languages based on grammar.	*Logical Positivism focused on the application of logic and on the philosophy of language to analyze scientific claims. Analysis void of contextual and contingent information produces a grammar that fixes criteria for observations.*	*The O/T distinction debate showed that our ordinary perceptual language is theory laden, what we see is influenced by what we believe. New theories leading to new tools and technologies greatly influenced the nature of observation in science and the representation of information and data.*	*What counts as observational shifts historically as science acquires new tools, technologies and theories. Science from the 1700s to the present has made a transition from a sense perception dominated study of nature to a tool, technology and theory-driven study of nature.*
4. Some form of inductive logic would be found that would provide a formal criterion for theory evaluation.	*There exists an algorithm for theory evaluation. Given a formal logical representation of the theory and data, the algorithm would provide the rational degree*	*Seeking an algorithm for a rational degree of confirmation is hopeless. Scientists working with the same data can rationally come to differing conclusions about which theory is best supported by given*	*Dialogue over the merits of competing data, models and theories is essential to the process of refining models and theories as well as accepting or rejecting them.*

	of confirmation the data confer on the theory.	*evidence. There is ongoing debate about how much variation is rational and how much is influenced by other factors.*	
5. Scientific theories can most usefully be thought of as sets of sentences in a formal language.	*Logical positivists advocated the position that theories are linguistic in character and could be described with deductive-nomological procedures.*	*Model-based views about the nature of science embrace, where hypothetical-deductive science does not, the dialogic complexities inherent in naturalized accounts of science. Scientific representations and explanations take many different forms: mathematical models, physical models, diagrams, computation models, etc.*	*Modern developments in science, mathematics, cognitive sciences, and computer sciences have extended the forms of representation in science well beyond strictly linguistic and logical formats. One widespread view is that theories should be thought of as families of models, and the models stand between empirical/conceptual evidence and theoretical explanations.*
6. Different scientific frameworks within the same domain are commensurable.	*Logical positivists sought to establish criteria that supported the claim that there are normative dimensions to scientific inquiry. The growth of scientific knowledge is a cumulative*	*Science communities are organized within disciplinary matrices. Shared exemplars help to define science communities. Scientific frameworks on different sides of a revolutionary change are incommensurable.*	*Different scientific frameworks within the same domain share some common ground. But they can disagree significantly on methodology, models and/or relevant data.* *The issue is the extent to which knowledge, beliefs, reasoning, representations, methods, and goals*

	process.	*Hypothesis testing takes place within more complex frameworks requiring more nuanced strategies for representing and reasoning with evidence.*	*from one research domain map to another research domain. The social and epistemic contexts are complex indeed.*
7. Scientific development is cumulatively progressive.	*Logical positivists held that the growth of scientific knowledge is cumulative and continually progressive. Scientists work with common theory choices.*	*Theory choice is an important dynamic of doing science and it influences how investigations are designed and conducted. On what grounds (e.g., rational vs. irrational) scientists make such choices is a matter for further research and debate.*	*The Kuhnian view that 'revolutions' involve the abandonment of established guiding conceptions and methods challenges the belief scientific development is always cumulatively progressive. New guiding conceptions inform what counts as an observation or a theory. Such changes reinforce beliefs that all scientific claims are revisable in principle. Thus, we embrace the notions of the 'tentativeness' of knowledge claims and the 'responsiveness' of scientific practices.*

Teaching NOS Explicitly – Version 1

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APPENDIX H – Understanding the Scientific Enterprise: The Nature of Science in the Next Generation Science Standards

Scientists and science teachers agree that science is a way of explaining the natural world. In common parlance, science is both a set of practices and the historical accumulation of knowledge. An essential part of science education is learning science and engineering practices and developing knowledge of the concepts that are foundational to science disciplines. Further, students should develop an understanding of the enterprise of science as a whole—the wondering, investigating, questioning, data collecting and analyzing. This final statement establishes a connection between the *Next Generation Science Standards* (NGSS) and the nature of science. Public comments on previous drafts of the NGSS called for more explicit discussion of how students can learn about the nature of science.

This chapter presents perspectives, a rationale and research supporting an emphasis on the nature of science in the context of the NGSS. Additionally, eight understandings with appropriate grade-level outcomes are included as extensions of the science and engineering practices and crosscutting concepts, not as a fourth dimension of standards. Finally, we discuss how to emphasize the nature of science in school programs.

The Framework for K-12 Science Education

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (NRC, 2012) acknowledged the importance of the nature of science in the statement "…there is a strong consensus about characteristics of the scientific enterprise that should be understood by an educated citizen" (NRC, 2012, page 78). The *Framework* reflected on the practices of science and returned to the nature of science in the following statement: "Epistemic knowledge is knowledge of the constructs and values that are intrinsic to science. Students need to understand what is meant, for example, by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them" (NRC, 2012, page 79). This quotation presents a series of concepts and activities important to understanding the nature of science as a complement to the practices imbedded in investigations, field studies, and experiments.

Nature of Science: A Perspective for the NGSS

The integration of scientific and engineering practices, disciplinary core ideas, and crosscutting concepts sets the stage for teaching and learning about the nature of science. This said, learning about the nature of science requires more than engaging in activities and conducting investigations.

When the three dimensions of the science standards are combined, one can ask what is central to the intersection of the scientific and engineering practices, disciplinary core ideas, and crosscutting concepts? Or, what is the relationship among the three basic elements of *A Framework for K-12 Science Education*? Humans have a need to know and understand the world around them. And they have the need to change their environment using technology in order to accommodate what they understand or desire. In some cases, the need to know originates in satisfying basic needs in the face of potential dangers. Sometimes it is a natural curiosity and, in other cases, the promise of a better, more comfortable life. Science is the pursuit of explanations of the natural world, and technology and engineering are means of accommodating human needs, intellectual curiosity and aspirations.

One fundamental goal for K-12 science education is a scientifically literate person who can understand the nature of scientific knowledge. Indeed, the only consistent characteristic of scientific knowledge across the disciplines is that scientific knowledge itself is open to revision in light of new evidence.

In K-12 classrooms, the issue is how to explain both the natural world and what constitutes the formation of adequate, evidence-based scientific explanations. To be clear, this perspective complements but is distinct from students engaging in scientific and engineering practices in order to enhance their knowledge and understanding of the natural world.

A Rationale and Research

Addressing the need for students to understand both the concepts and practices of science and the nature of science is not new in American education. The writings of James B. Conant in the 1940s and 50s, for example, argue for a greater understanding of science by citizens (Conant, 1947). In *Science and Common Senses* (1951), Conant discusses the “bewilderment of laymen” when it comes to understanding what science can and cannot accomplish, both in the detailed context of investigations and larger perspective of understanding science. Conant says: “…The remedy does not lie in a greater dissemination of scientific information among nonscientists. Being well informed about science is not the same thing as understanding science, though the two propositions are not antithetical. What is needed is methods for importing some knowledge of the tactics and strategy of science to those who are not scientists” (Conant, 1951, page 4). In the context of the discussion here, tactics are analogous to science and engineering practices, as well as to the nature of scientific explanations.

The present discussion recommends the aforementioned “tactics of science and engineering practices and crosscutting concepts” to develop students’ understanding of the larger strategies of the scientific enterprise—the nature of scientific explanations. One should note that Conant and colleagues went on to develop *Harvard Cases in History of Science*, a historical approach to understanding science. An extension of the nature of science as a learning goal for education soon followed the original work at Harvard. In the late 1950s, Leo Klopfer adapted the *Harvard Cases* for use in high schools (Klopfer & Cooley, 1963). Work on the nature of science has continued with lines of research by Lederman (1992), Lederman and colleagues (Lederman et al., 2002), and Duschl (1990; 2000; 2008). One should note that one aspect of this research base addresses the teaching of the nature of science (see, e.g., Lederman & Lederman, 2004; Flick & Lederman, 2004; Duschl, 1990; McComus, 1998; Osborne et al., 2003; Duschl & Grandy, 2008).

Further support for teaching about the nature of science can be seen in 40 years of Position Statements from the National Science Teachers Association (NSTA). In the late 1980s, *Science for All Americans* (Rutherford & Ahlgren, 1989), the 1990s policy statement *Benchmarks for Science Literacy* (AAAS, 1993), and *National Science*

Education Standards (NRC, 1996) clearly set the understanding of the nature of science as a learning outcome in science education.

Recently, discussions of *A Framework for K-12 Science Education* (NRC, 2012) and implications for teaching science have provided background for instructional strategies that connect specific practices and the nature of scientific explanations (Duschl, 2012; Krajcik & Merritt, 2012; Reiser, Berland, & Kenyon, 2012).

The Nature of Science and NGSS

The nature of science is included in the *Next Generation Science Standards*. Here we present the NOS Matrix. The basic understandings about the nature of science are:

- Scientific Investigations Use a Variety of Methods
- Scientific Knowledge is Based on Empirical Evidence
- Scientific Knowledge is Open to Revision in Light of New Evidence
- Scientific Models, Laws, Mechanisms, and Theories Explain Natural Phenomena
- Science is a Way of Knowing
- Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science is a Human Endeavor
- Science Addresses Questions About the Natural and Material World

The first four of these understandings are closely associated with practices and the second four with crosscutting concepts. The NOS Matrix presents specific content for K-2, 3-5, middle school and high school. Appropriate learning outcomes for the nature of science are expressed in the performance expectations, and presented in either the foundations column for practices or crosscutting concepts of the DCI standard pages.

Again, one should note that the inclusion of nature of science in NGSS does not constitute a fourth dimension of standards. Rather, the grade level representations of the eight understandings have been incorporated in the practices and crosscutting concepts, as seen in the performance expectations and represented in the foundation boxes.

Overview

One goal of science education is to help students understand the nature of scientific knowledge. This matrix presents eight major themes and grade level understandings about the nature of science. Four themes extend the scientific and engineering practices and four themes extend the crosscutting concepts. These eight themes are presented in the left column. The matrix describes learning outcomes for the themes at grade bands for K-2, 3-5, middle school, and high school. Appropriate learning outcomes are expressed in selected performance expectations and presented in the foundation boxes throughout the standards.

Understandings about the Nature of Science

Categories	K-2	3-5	Middle School	High School
Scientific Investigations Use a Variety of Methods	▪ Science investigations begin with a question. ▪ Science uses different ways to study the world.	▪ Science methods are determined by questions. ▪ Science investigations use a variety of methods, tools, and techniques.	▪ Science investigations use a variety of methods and tools to make measurements and observations. ▪ Science investigations are guided by a set of values to ensure accuracy of measurements, observations, and objectivity of findings. ▪ Science depends on evaluating proposed explanations. ▪ Scientific values function as criteria in distinguishing between science and non-science.	▪ Science investigations use diverse methods and do not always use the same set of procedures to obtain data. ▪ New technologies advance scientific knowledge. ▪ Scientific inquiry is characterized by a common set of values that include: logical thinking, precision, open-mindedness, objectivity, skepticism, replicability of results, and honest and ethical reporting of findings. ▪ The discourse practices of science are organized around disciplinary domains that share exemplars for making decisions regarding the values, instruments, methods, models, and evidence to adopt and use. ▪ Scientific investigations use a variety of methods, tools, and techniques to revise and produce new knowledge.
Scientific Knowledge is Based on Empirical Evidence	▪ Scientists look for patterns and order when making observations about the world.	▪ Science findings are based on recognizing patterns. ▪ Science uses tools and technologies to make accurate measurements and observations.	▪ Science knowledge is based upon logical and conceptual connections between evidence and explanations. ▪ Science disciplines share common rules of obtaining and evaluating empirical evidence.	▪ Science knowledge is based on empirical evidence. ▪ Science disciplines share common rules of evidence used to evaluate explanations about natural systems. ▪ Science includes the process of coordinating patterns of evidence with current theory. ▪ Science arguments are strengthened by multiple lines of evidence supporting a single explanation.
Scientific Knowledge is Open to Revision in Light of New Evidence	▪ Science knowledge can change when new information is found.	▪ Science explanations can change based on new evidence.	▪ Scientific explanations are subject to revision and improvement in light of new evidence. ▪ The certainty and durability of science findings varies. ▪ Science findings are frequently revised and/or reinterpreted based on new evidence.	▪ Scientific explanations can be probabilistic. ▪ Most scientific knowledge is quite durable but is, in principle, subject to change based on new evidence and/or reinterpretation of existing evidence. ▪ Scientific argumentation is a mode of logical discourse used to clarify the strength of relationships between ideas and evidence that may result in revision of an explanation.
Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena	▪ Science uses drawings, sketches, and models as a way to communicate ideas. ▪ Science searches for cause and effect relationships to explain natural events.	▪ Science theories are based on a body of evidence and many tests. ▪ Science explanations describe the mechanisms for natural events.	▪ Theories are explanations for observable phenomena. ▪ Science theories are based on a body of evidence developed over time. ▪ Laws are regularities or mathematical descriptions of natural phenomena. ▪ A hypothesis is used by scientists as an idea that may contribute important new knowledge for the evaluation of a scientific theory. ▪ The term "theory" as used in science is very different from the common use outside of science.	▪ Theories and laws provide explanations in science, but theories do not with time become laws or facts. ▪ A scientific theory is a substantiated explanation of some aspect of the natural world, based on a body of facts that has been repeatedly confirmed through observation and experiment, and the science community validates each theory before it is accepted. If new evidence is discovered that the theory does not accommodate, the theory is generally modified in light of this new evidence. ▪ Models, mechanisms, and explanations collectively serve as tools in the development of a scientific theory. ▪ Laws are statements or descriptions of the relationships among observable phenomena. ▪ Scientists often use hypotheses to develop and test theories and explanations.

Understandings about the Nature of Science

Categories	K-2	3-5	Middle School	High School
Science is a Way of Knowing	▪ Science knowledge helps us know about the world.	▪ Science is both a body of knowledge and processes that add new knowledge. ▪ Science is a way of knowing that is used by many people.	▪ Science is both a body of knowledge and the processes and practices used to add to that body of knowledge. ▪ Science knowledge is cumulative and many people, from many generations and nations, have contributed to science knowledge. ▪ Science is a way of knowing used by many people, not just scientists.	▪ Science is both a body of knowledge that represents a current understanding of natural systems and the processes used to refine, elaborate, revise, and extend this knowledge. ▪ Science is a unique way of knowing and there are other ways of knowing. ▪ Science distinguishes itself from other ways of knowing through use of empirical standards, logical arguments, and skeptical review. ▪ Science knowledge has a history that includes the refinement of, and changes to, theories, ideas, and beliefs over time.
Scientific Knowledge Assumes an Order and Consistency in Natural Systems	▪ Science assumes natural events happen today as they happened in the past. ▪ Many events are repeated.	▪ Science assumes consistent patterns in natural systems. ▪ Basic laws of nature are the same everywhere in the universe.	▪ Science assumes that objects and events in natural systems occur in consistent patterns that are understandable through measurement and observation. ▪ Science carefully considers and evaluates anomalies in data and evidence.	▪ Scientific knowledge is based on the assumption that natural laws operate today as they did in the past and they will continue to do so in the future. ▪ Science assumes the universe is a vast single system in which basic laws are consistent.
Science is a Human Endeavor	▪ People have practiced science for a long time. ▪ Men and women of diverse backgrounds are scientists and engineers.	▪ Men and women from all cultures and backgrounds choose careers as scientists and engineers. ▪ Most scientists and engineers work in teams. ▪ Science affects everyday life. ▪ Creativity and imagination are important to science.	▪ Men and women from different social, cultural, and ethnic backgrounds work as scientists and engineers. ▪ Scientists and engineers rely on human qualities such as persistence, precision, reasoning, logic, imagination and creativity. ▪ Scientists and engineers are guided by habits of mind such as intellectual honesty, tolerance of ambiguity, skepticism and openness to new ideas. ▪ Advances in technology influence the progress of science and science has influenced advances in technology.	▪ Scientific knowledge is a result of human endeavor, imagination, and creativity. ▪ Individuals and teams from many nations and cultures have contributed to science and to advances in engineering. ▪ Scientists' backgrounds, theoretical commitments, and fields of endeavor influence the nature of their findings. ▪ Technological advances have influenced the progress of science and science has influenced advances in technology. ▪ Science and engineering are influenced by society and society is influenced by science and engineering.
Science Addresses Questions About the Natural and Material World.	▪ Scientists study the natural and material world.	▪ Science findings are limited to what can be answered with empirical evidence.	▪ Scientific knowledge is constrained by human capacity, technology, and materials. ▪ Science limits its explanations to systems that lend themselves to observation and empirical evidence. ▪ Science knowledge can describe consequences of actions but is not responsible for society's decisions.	▪ Not all questions can be answered by science. ▪ Science and technology may raise ethical issues for which science, by itself, does not provide answers and solutions. ▪ Science knowledge indicates what can happen in natural systems—not what should happen. The latter involves ethics, values, and human decisions about the use of knowledge. ▪ Many decisions are **not** made using science alone, but rely on social and cultural contexts to resolve issues.

🟦 Nature of Science understandings most closely associated with Practices

🟩 Nature of Science understandings most closely associated with Crosscutting Concepts

Implementing Instruction to Facilitate Understanding of the Nature of Science

Now, the science teacher's question: How do I put the elements of practices and crosscutting concepts together to help students understand the nature of science? Suppose students observe the moon's movements in the sky, changes in seasons, phase changes in water, or life cycles of organisms. One can have them observe patterns and propose explanations of cause-effect. Then, the students can develop a model of the system based on their proposed explanation. Next, they design an investigation to test the model. In designing the investigation, they have to gather data and analyze data. Next, they construct an explanation using an evidence-based argument. These experiences allow students to use their knowledge of the practices and crosscutting concepts to understand the nature of science. This is possible when students have instruction that emphasizes why explanations are based on evidence, that the phenomena they observe are consistent with the way the entire universe continues to operate, and that we can use multiple ways to investigate these phenomena.

The Framework emphasizes that students must have the opportunity to stand back and reflect on how the practices contribute to the accumulation of scientific knowledge. This means, for example, that when students carry out an investigation, develop models, articulate questions, or engage in arguments, they should have opportunities to think about what they have done and why. They should be given opportunities to compare their own approaches to those of other students or professional scientists. Through this kind of reflection they can come to understand the importance of each practice and develop a nuanced appreciation of the nature of science.

Using examples from the history of science is another method for presenting the nature of science. It is one thing to develop the practices and crosscutting concepts in the context of core disciplinary ideas; it is another aim to develop an understanding of the nature of science within those contexts. The use of case studies from the history of science provides contexts in which to develop students' understanding of the nature of science. In the middle and high school grades, for example, case studies on the following topics might be used to broaden and deepen understanding about the nature of science.

- Copernican Resolution
- Newtonian Mechanics
- Lyell's Study of Patterns of Rocks and Fossils
- Progression from Continental Drift to Plate Tectonics

- Lavoisier/Dalton and Atomic Structure
- Darwin Theory of Biological Evolution and the Modern Synthesis
- Pasteur and the Germ Theory of Disease
- James Watson and Francis Crick and the Molecular Model of Genetics

These explanations could be supplemented with other cases from history. The point is to provide an instructional context that bridges tactics and strategies with practices and the nature of science, through understanding the role of systems, models, patterns, cause and effect, the analysis and interpretations of data, the importance of evidence with scientific arguments, and the construction of scientific explanations of the natural world. Through the use of historical and contemporary case studies, students can understand the nature of explanations in the larger context of scientific models, laws, mechanisms, and theories.

In designing instruction, deliberate choices will need to be made about when it is sufficient to build students' understanding of the scientific enterprise through reflection on their own investigations, and when it is necessary and productive to have students analyze historical case studies.

Conclusion

This discussion addressed how to support the development of an understanding of the nature of science in the context of the *Next Generation Science Standards*. The approach centered on eight understandings for the nature of science and the intersection of those understandings with science and engineering practices, disciplinary core ideas, and crosscutting concepts. The nature of the scientific explanations is an idea central to standards-based science programs. Beginning with the practices, core ideas, and crosscutting concepts, science teachers can progress to the regularities of laws, the importance of evidence, and the formulation of theories in science. With the addition of historical examples, the nature of scientific explanations assumes a human face and is recognized as an ever-changing enterprise.

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