Reconsidering the Character and Role of Inquiry in School Science: Analysis of a Conference[1][2]

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Introduction

This is a report of an NSF sponsored conference we organized whose purpose was to provide a structure for discussion of science education with the goal of summarizing and synthesizing developments in three domains

(1) science studies, e.g., history, philosophy and sociology of science

(2) the learning sciences, e.g., cognitive science, philosophy of mind, educational psychology, social psychology, computer sciences, linguistics, and

(3) educational research focusing on the design of learning environments that promote inquiry and that facilitate dynamic assessments.

These three domains have reshaped our thinking about the role that inquiry has in science education programs. Over the past 50 years there have been dynamic changes in our conceptualizations of science, of learning, and of science learning environments. Such changes have important implications for how we interpret (1) the role of inquiry in K-12 science education programs and (2) the design of curriculum, instruction, and assessment models that strive to meet the NSES inquiry goals:

- Students should learn to do scientific inquiry.
- Students should develop an understanding of scientific inquiry.

Although these domains have undergone closely related changes, the communication among them has been very partial and haphazard. The point of our conference was to provide a rich structure for interaction. We wrote a plenary paper, which was circulated before hand, and discussed the first evening. On each of the following two days there were four main papers, each with a commentator, followed at the end of the day by a four person panel. Day one was devoted to Philosophical Issues and Next Steps for Research, and day two to Policy, Practice and Next Steps for Educational Research. The conference participants included philosophers, psychologists and educational researchers. (The list of participants and their paper titles is in Appendix A--more complete information, including the papers and comments can be located at the conference website http://www.ruf.rice.edu/~rgrandy/ConferenceInfo.html.

Background

The commitment to inquiry and to lab investigation is a hallmark of USA science education. The development of curriculum materials that would engage students in the doing of science though required an investment in the infrastructure of schools for the building of science labs and for the training of teachers. What is important to note is that at the same period (1955 to 1970) when scientists were leading the revamping of science education to embrace inquiry approaches, historians and philosophers of science were revamping ideas about the nature of scientific inquiry and cognitive psychologists were revamping ideas about learning. A reconsideration of the role of inquiry in school science, it can be argued, began approximately 50 years ago.

Unfortunately, the widespread reconsideration has also led to a proliferation of meanings associated with "inquiry". In a recent international set of symposium papers (Abd-El-Khalick, et al, 2004), the following terms and phrases were used to characterize inquiry:

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• scientific processes
• scientific method
• experimental approach
• problem solving
• conceiving problems
• formulating hypotheses
• designing experiments
• gathering and analyzing data
• drawing conclusions
• deriving conceptual understandings
• examining the limitations of scientific explanations
• methodological strategies
• knowledge as "temporary truths
• practical work
• finding and exploring questions
• independent thinking
• creative inventing abilities
• hands-on activities

Whereas the "science for scientists" approach to science education stressed teaching what we know and what methods to use, the new views of science and of psychology raise pressing issues of how we know what we know and why we believe certain statements rather than competing alternatives. The shift was a move from a curriculum position that asks, "what do we want students to know and what do they need to do to know it", to a curriculum position that asks, "what do we want students to be able to do and what do they need to know to do it". The *National Science Education Standards* content goals for inquiry focus on student's abilities to pursue inquiry and to understand the nature of scientific inquiry. But once again we seem to find ourselves in the situation were science education has not kept pace with developments in science. Science education continues to be dominated by hypothetico-deductive views of science while philosophers of science have shown that scientific inquiry has other equally essential elements: theory development, conceptual change, and model-construction. This is not to imply that scientists no longer engage in experiments. Rather, the role of experiments is situated in theory and model building, testing and revising, and the character of experiments is situated in how we choose to conduct observations and measurements; i.e., data collection. The danger is privileging one aspect of doing science to the exclusion of others.

Despite agreement that important changes have taken place in educational practices, and a loose consensus that educational practice can be improved by using extended instructional sequences variously called immersion units/problem base learning/full inquiry, it is unclear more precisely what the character of these sequences should be. For the purposes of this brief paper, we will assume that immersion units and problem-based learning are forms of full inquiry and will work at the problem of clarifying "inquiry". We also want to identify significant areas of dissensus and begin to analyze which of these are areas of disagreement about empirical issues on which more research needs to be done and which areas may represent differences in fundamental values. Since the term "***inquiry***" appears in the *NSE Standards* and is also central to the AAAS *Benchmarks for Science Literacy*, we have chosen to focus on that term and to attempt to clarify what is involved.

Consensus on Inquiry

As a general summary of the consensus that emerged through the papers, comments and discussions, the there are three large-scale points. The first is that although traditional methods and inquiry teaching agree on the importance of:

• The **conceptual** structures and **cognitive** processes used when reasoning about scientific topics, the traditional conceptions, built on **The Scientific Method** (as presented on inside covers of science texts) greatly oversimplify the nature of observation and theory and almost entirely ignores the role of models in the conceptual structure of science.

However, while traditional methods have too narrow a conception of the cognitive structures involved in scientific reasoning, they almost entirely ignore both

• The **epistemic** frameworks used when developing and evaluating scientific knowledge, and,

• The **social** processes and contexts that shape how knowledge is discovered, communicated, represented, and argued.

We began the conference with a moderately long list of aspects of science that we thought inquiry should include, and almost every speaker and commentator said, in effect, "yes, but you also need to include ...".

Our current list of aspects of scientific inquiry includes:

posing questions
refining questions
evaluating questions
designing experiments
refining experiments
interpreting experiments
making observations
collecting data
representing data
analyzing data
relating data to hypotheses/models/theories
formulating hypotheses
learning theories
learning models
refining theories
refining models
comparing alternative theories/models with data
providing explanations
giving arguments for/against models and theories
comparing alternative models
making predictions
recording data
organizing data
discussing data
discussing theories/models
explaining theories/models
writing about data
writing about theories/models
reading about data
reading about theories/models

If we contrast this list with the traditional Scientific Method:

1. Make observations
2. Formulate a hypothesis
3. Deduce consequences from the hypothesis
4. Make observations to test the consequences
5. Accept or reject the hypothesis based on the observations.

we can see that although all of these involve cognitive tasks, only the last involves an epistemic task. In contrast, many of the activities on our list include social or epistemic elements. In fact, many of the items on the list involve all three.

For example, writing about a theory is obviously a cognitive task, but it also requires social judgment since the writer is writing for an audience (Norris, 2005). Writing for an audience means that the writer must have a nuanced and detailed conception of what the belief and motivational structures of the reader are. If the writer does not engage the motivational structure of the reader, the reader will read superficially if at all. If the writer does not engage the readers' belief structure in a relevant way, the readers' beliefs will not change and the reader may not even pay attention to the arguments. And the task is also epistemic because the presumptive point of the writing is to adduce evidence that will encourage belief in or doubt about the theory and so it is essential to the writing task that one makes epistemic judgments about the relations between evidence and theory.

Similarly, although one can formulate ideas in solitude, if you are part of a scientific or classroom community in which there is an ongoing discussion of a question against a background of shared theoretical assumptions, then what counts as a relevant conjecture, inference or hypothesis is constrained by social and epistemic considerations. One of the items on which there was a strong consensus was that an important element of science education involves the learners developing a sense of when a hypothesis or theory is a scientific one. There was disagreement, however, on how explicitly this can or cannot be taught and on how explicitly the criteria can be formulated. We will return to this later in the context of discussing an expanded notion of scientific method.

Clearly not every 50 minutes of a science class can include all of the elements on our inquiry list, and even an extended unit may not be able to include all of these, but our consensus is that it is important to keep your eye on the big list. In choosing from the list, it is important that consideration be given to the social and epistemic elements of tasks, in addition to the cognitive. Since we have consensus that all of these are part of "authentic science", and that they cannot all always be included in the classroom, it leads to the task of characterizing what is the optimal "school science". (Cf. Brickhouse, 2005b for further discussion)

Designing School Science

A number of our participants, especially Bordeaux, Edelson, Gitomer and Schauble emphasized that we are discussing an engineering design task. Our goals are to design curricula and environments for students and for teachers that promote student learning. The first two questions to ask about an engineering problem are:

What is the goal?
What are the constraints?

There were two goals that emerged through our discussions. The first, the more traditional, is to have students acquire knowledge of the "content" of science, the second is for them to learn the "nature" of science. We will return later to difficult questions about the relation between these questions, but it is important to put them out front as we discuss constraints.

There are two kinds of constraints on the engineering design project: The first is the cognitive limitations of the learners at various ages. There has been heated discussion generated by Gopnik's claim that children are "little scientists", and this topic was directly addressed at the beginning of our conference (Brewer 2005, Schauble, 2005). There was consensus that children are like scientists in that they notice at lest some regularities and pose hypothesis. However, there was also consensus that children are (at least initially) unlike scientists because:

- children have no social structure to support inquiry
- scientists have strong motivations for inquiry
- scientists actively look for evidence
- scientists read about data and theories/models
- scientists write about data and theories/models
- scientists debate the merits of theories/models
- scientific theories/models typically invoke hidden or not directly observable variables, entities and processes
- scientific theories/models are constrained by related theories and models
- scientific theories often rely on mathematics to represent data
- scientific theories often rely on mathematics to represent models/theories
- scientists evaluate theories/models against evidence

Given this consensus, which follows from the earlier consensus on inquiry and our reflections on children's abilities, the consequence is clear. We need curricula, teachers and environments in which children can develop the capacities to carry out these cognitive activities. The constraints on time, teacher training, classroom environments and school culture are the second kind of constraint and will be discussed in detail later.

There was a consensus, following from the discussions above, that with respect to learning in an inquiry environment, we want learners to initiate and take responsibility for as many of the activities in Table 1 as possible. For learners who are not yet capable of taking full responsibility, the teacher (or perhaps other students in a group) must take more of the initiative. Designing an inquiry curriculum for the long term means thinking about how to shift the classroom environment from the right hand side of the table below toward the left. We want to emphasize that the rate at which this can be done will vary from learner to learner, as well as from row to row, and that some of the rows will depend on others. We will discuss in a later section the very important fact that the ability to carry out the activities listed on the right are often beyond the current capabilities of some science teachers.

In many cases we want to build on prior student abilities. For example, in the first row, we know that students at an early age spontaneously generate questions, but those questions are not necessarily scientific. Unfortunately, what happens in many classroom environments is that instead of learning to only ask the scientific questions, students stop asking questions at all.

There was also consensus that although we have some idea what learners are capable of we lack systematic extensive research of what is possible given a consistent and thorough full inquiry curriculum starting in kindergarten. In particular, our consensus list includes makes central various activities involving models, none of which are even mentioned in the traditional "Scientific Method".

In our plenary paper we trace in some detail the progression from the logical positivist hypothetico-deductive notion of scientific method, through the more historically oriented conceptions of Kuhn and similar thinkers to a post-Kuhnian era which embraces some of Kuhn's ideas, but rejects or remains skeptical about others. The recognition of models is part of the post-Kuhnian change in philosophy of science. This most recent movements in philosophy of science can be seen as filling in some of the gaps left by Kuhn's critique of the basic tenets of logical positivism--a topic we will take up in some detail later. This movement:

1. Emphasizes the role of models and data construction in the scientific process and demotes the role of theory.
2. Sees the scientific community as an essential part of the scientific process
3. Sees the cognitive scientific processes as a distributed system that includes instruments.

Among the major figures in this movement are Nancy Cartwright (1983), Ron Giere (1988, 1999), Helen Longino (1990,2002) Nancy Nersessian (1999), Patrick Suppe (1969), Fred Suppes (1989), and others.

The term "model", like inquiry, has multiple meanings. As with "inquiry" we recommend an inclusive use of the term "model". Models can include:

mathematical models	computer models
physical models	visual or pictorial models
analogical models	

Our taxonomy of models and their apparently disparate nature might lead readers to wonder if anything unites them other than the label, indeed in discussion one of our participants argued that 'model' is not a 'natural kind' concept. We agree, but we believe that 'model' is a functional kind. Natural kinds are concepts such as specific species and chemical elements, where there is a great deal of commonality of physical structure among the various instances. Functional kinds are defined in terms of the function they perform and need not have structural similarities. For example, there is little physical similarity between water clocks, mechanical clocks and digital clocks--but they all serve the same function of providing a visual representation of the passage of time.

We believe that the common element to all models is that they are external aids to reasoning. They are primarily cognitive prostheses, but they also serve social and epistemic ends. Mathematical models provide means of manipulating data or information to get predictions or explanations. Each of the different kinds does this in a different medium. Moreover, just as we now conceive the scientific community as a fundamental part of the process, the models are also a fundamental part and the cognitive processes should be thought of as being distributed throughout the system of people, instruments and models. (Hutchins, 1995) (Giere, 2002) It is also important to understand that although these are (at least) five different kinds of models, they can be combined. Maxwell (Nersessian, 2005) used a visual representation of an imagined physical model to derive a mathematical description of the electromagnetic field. (See Duschl & Grandy, 2005, or Grandy, 2003 for further discussion.)

Toward an Enhanced Version of a Scientific Method

Developments in scientific theory, 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 that inquiry. Once scientific inquiry was principally the domain of unaided sense perception, today it 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).

Historically, scientific inquiry has often been motivated by practical concerns, e.g., improvements in astronomy were largely driven and financed by the quest for a better calendar, and thermodynamics was primarily motivated by the desire for more efficient steam engines. But today scientific inquiry underpins the development of vastly more powerful new technologies and addresses more pressing social problems, e. g., finding clean renewable energy sources, feeding an exploding world population through genetically modified food technologies; stem cell research. In such pragmatic problem-based contexts, new scientific knowledge is as much a consequence of inquiry as the goal of inquiry.

One can summarize 20th century developments in philosophy of science along a continuum where science has been conceived as an experiment-driven enterprise, a theory-driven enterprise, and a model-driven enterprise. The experiment-driven enterprise gave birth to the movements called logical positivism or logical empiricism, shaped the development of analytic philosophy and gave rise to the hypothetico-deductive conception of science. The image of scientific inquiry was that experiment led to new knowledge that accrued to established knowledge. How knowledge was discovered and refined was not the philosophical agenda, only the justification of knowledge was deemed important. This early 20th century perspective is referred to as the 'received view' of philosophy of science.

This 'received view' conception of science is closely related to traditional explanations of "the scientific method." The steps in the method are:

1. Make observations
2. Formulate a hypothesis
3. Deduce consequences from the hypothesis
4. Make observations to test the consequences
5. Accept or reject the hypothesis based on the observations.

In the paragraphs to follow, we discuss how theory-driven and model-driven views of the science contribute to an expanded notion of the scientific method. It is important, however, not to simply reject logical positivism without understanding it. If we do so we risk both losing some of the insights and losing perspective on some of the oversimplifications that were involved. Similarly, we do not want to reject this conception of scientific method, but to radically supplement it.

<u>7 Tenets</u>

We find it helpful to identify *7 tenets* that underlie logical positivism. Reactions and objections to the *7 tenets* have identified limitations to logical positivism and thereby expanded our perspectives about the nature of science, the growth of scientific knowledge, and the goals/limitations of science. With respect to school science, we examine how supplemented versions of the *7 tenets* can guide thinking about (1) the design of science education frameworks; (2) an enhanced notion of scientific method for school scientific inquiry. The *7 tenets* are:

1. 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.
2. Some form of inductive logic would be found that would provide a formal criterion for theory evaluation,
3. There is an important dichotomy between contexts of discovery and contexts of justification
4. The individual scientist is the basic unit of analysis for understanding science
5. Different scientific frameworks are commensurable.
6. Scientific development is cumulatively progressive.
7. Scientific theories can most usefully be thought of as sets of sentences in a formal language.

Tenet 1 posits a linguistic distinction between theoretical and observational terms in the languages of science. Over the years both in terms of internal developments in logical positivism and external criticisms philosophers of science recognized that the theory/observation language distinction can't be made on the basis of grammar alone. One of the most important external critics was Norwood Russell Hanson with his 1958 book *Patterns of Discovery*. The O/T distinction debate has led to the recognition that our ordinary perceptual language is theory laden, what we see is influenced by what we know. Logical positivists were slow to recognize the shift in what counts as observational, which is not a matter of grammar but rather evolves historically as science changes with respect to new tools, technologies and theories (Nersessian, 2005; Solomon, 2005).

Moreover, scientists themselves describe the processes in terms that suit their goals. For example, when Rutherford discovered that atoms consist of nuclei and electrons which are each very small in relation to the size of the atom, he described the experiment as shooting electrons at a thin sheet of gold foil and *seeing* that most electrons pass through but some bounce straight back. Millikan (1965) in describing his classic oil drop experiment in which he measured the charge on the electron speaks also of *seeing* individual electrons. We would regard these as metaphorical, perhaps, but there is no question that from 1900 to 2000 science progressed from a stage where the existence of atoms was a debatable hypothesis to one where we can capture images of individual atoms and we can manipulate them individually. The implication for school science is the need to engage in dialectical processes regarding which theoretical frameworks are being used as guiding conceptions when critiquing or making decisions about what data to collect, what questions to ask, what data to use as evidence, among others.

Tenet 2, the belief in inductive logic, was important as part of the conception of scientific rationality specifically with respect to theory evaluation. Based on the success of logical positivism in developing a deductive logic that was adequate for almost all mathematical purposes, the positivists saw it as a natural extension to provide an inductive logic for theory evaluation. The goal of Carnap, Hempel, Reichenbach and others was to provide an algorithm for theory evaluation. The idea was that given a formal representation of the theory and a formal representation of the data, the algorithm would provide *the rational degree of confirmation* the data confer on the theory. This would mean that given two scientists, if they were confronted with the same data, if they were rational, then they would agree on the exact extent to which the data confirmed a given theory. For many reasons, this program is now uniformly agreed to be hopeless. It is recognized instead that rational scientists working with the same data can come to differing conclusions about the degree of confirmation of a theory by given evidence, and indeed that dialogue over the merits of alternative models and theories is essential to the process of refining models and theories as well as accepting or rejecting them. There is ongoing debate about how much variation is rational and how much is bias--Longino(1990, 2000) and Solomon (2001, 2005) and Brickhouse (2005) are focused centrally on this topic.

The implication for school science is the need to engage learners in the development of critieria for theory/explanation evaluation. Furthermore, there is the need to have learners consider alternative explanations and participate in dialogical activities that debate and argue the merits of the alternative models and theories. Conference papers from Kelly (2005) Chinn (2005), Edelson (2005) and the respective commentaries by Rudolph (2005), Krajick (2005) and Bordeaux (2005) shed light on how to frame the criteria and the dialogical processes.

Tenet 3 was made explicit in Reichenbach (), but was an assumption earlier. It has been criticized by theory-change advocates as a way to attack logical positivism's exclusive focus on the final products or outcomes of science. Equally important for the theory change advocates was developing an understanding of the processes regarding how the growth of knowledge begins. What we now see as problematic is the exclusive emphasis on the 'end points' of the growth of knowledge continuum; e.g., the context of discovery as the situation in which a theory is first discovered, and the context of justification as the presentation of the theory in its final axiomatized form. Perhaps the most important element Kuhn and others added to the problem mix is the recognition that most of the theory change that occurs in science is not final theory acceptance, but improvement and refinement of a theory. Ninety-nine percent of what occurs in science is neither the context of discovery nor the context of justification, but the context of theory development, of conceptual modification. The dialogical processes of theory development and of dealing with anomalous data occupy a great deal of scientists' time and energy.

The implication for school science is the need to provide opportunities for students to engage in the growth of scientific knowledge (Kelly, 2005; Rudolph, 2005; Hammer, 2005; Sandoval, 2005), a process that reveals the ways in which scientists respond to new data, to new theories that interpret data, or to both. Some proponents of teaching the nature of science describe this feature of the scientific process by saying that scientific claims are tentative. Taking a dialectical orientation to school science the preference is to say that science and scientists are *responsive*, thus avoiding the connotation that 'tentative' claims are unsupported by evidence or scientific reasoning.

Tenets 4, 5 and 6 of logical positivism all came under attack by Norwood Hanson's challenge on the observational/theoretical distinction (Tenet 1) and Thomas Kuhn's ideas about theory change involving a disciplinary matrix. This is an elaboration of the point made above that there are important practices occurring between the discovery and justification end points of science: an example is the role of abduction in scientific reasoning. Kuhn's inclusion of the scientific community as part of the scientific process goes against Tenet 4 above, which treats the individual scientist as the basic unit for understanding scientific rationality. The idea of research groups or communities of practice being the unit of scientific discourse produced negative reactions from many philosophers because including a social dimension was seen as threatening the objectivity and rationality of scientific development. The fear is that this represents 'mob psychology' and not rationality and reason ruling the growth of scientific knowledge. However, research examining the cognitive, epistemic and social dynamics of research groups (Dunbar, 1995, Solomon, 2001), and of research programs (Thagard, 1994; Pickering, 1992), provides evidence that there are important dialogic processes taking place as knowledge claims and beliefs are posited and justified. Scientific inquiry involves a complex set of discourse processes.

Kuhn's arguments that disciplinary matrices on different sides of a revolutionary change are incommensurable challenged Tenet 5 and also produced negative reactions from philosophers of science. The issue here is to what extent may one claim that there are normative dimensions to scientific inquiry. That is, can knowledge, beliefs, reasoning, representations, methods, and goals from one research domain map to another research domain. On what criteria can one claim common ground or can one claim separate ground. The social and epistemic contexts are complex indeed (Solomon, 2005; Brickhouse, 2005).

The challenges to Tenets 4 and 5 speak to the deepened understanding of the complexity of doing science. New tools and technologies that were an outgrowth of successful theoretical scientific frameworks (e.g., electromagnetic spectrum, solid state physics) greatly influenced the nature of observation in science and the representation of information and data. 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-laden study of nature. While hypothesis testing has been and always will be a corner stone of science, today hypothesis testing takes place within more complex frameworks requiring more nuanced strategies for representing and reasoning with evidence. The nuanced strategies more often than not are not rule driven but rather emerge from the dialogical or dialectical practices of science. Challenges to Tenets 4 and 5 highlight the importance of the social dimensions of science: the representation, communication and argumentation practices (Longino, 1990, Solomon 2001,2005). Attention to the theoretical or model-based frameworks that provide the guiding conceptions for all aspects of scientific inquiry as well as the foundation for engagement in discourse practices is missing from school science (Chinn & Samarapungavan, 2005; Windshitl, 2005).

Tenet 6 claims that scientific development is cumulatively progressive. The Kuhnian challenge that 'revolutions' shift the guiding conceptions of science to new original domains of inquiry is based on epistemological grounds. What comes to count as an observation or a theory and on what grounds raises questions and implications regarding the 'tentativeness' of knowledge claims and the 'responsiveness' of scientific practices. Theory choice is an important dynamic of doing science. On what grounds (e.g., rational vs. irrational) scientists make such choices is a matter of great debate. Much attention has been given to how children's guiding conceptions can obstruct science learning or facilitate conceptual change learning. The educational debate centers on whether conceptions are parts of theory-like schema that can inhibit cognitive processes or are component parts of knowledge systems within which their use needs to be flexible as the knowledge system itself develops. The implication for school science is that learners need to engage in the examination of alternative explanations and guiding conceptions when developing accounts of phenomena and mechanisms. Subsequently, room needs to be allocated in the curriculum for learners to engage in serious discussions about the criteria that are used to assess and make judgments about knowledge claims.

The 7th tenet of logical positivism states that theories are best thought of as sets of sentences in a formal language. While a linguistic basis is sometimes necessary, it is far from sufficient. 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 (Nersessian, 2005). Model-based views about the nature of science embrace, where H-D science does not, the dialogic complexities inherent in naturalized accounts of science. Functional and pragmatic parameters are important considerations for describing and understanding the growth of scientific knowledge and the accompanying methods of scientific inquiry.

Looking across all *7 tenets,* the bold implication for school science is the need to consider developing an expanded notion for the scientific method. The expanded scientific method (SMe) 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: H-D experiment driven science; Conceptual Change theory driven science; Model-based driven science. The consensus of the conference participants was 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.

One area of dissensus for contemporary science education practice concerns how best to develop learners' understanding of the nature of science (Abd-El-Khalick, 2005). There are two kinds of disagreement, one about NOS itself, the other about how to teach it. With respect to teaching NOS one prominent approach is to postulate a generic list of things to know about the NOS and then design discrete lessons that examine each of the elements to support reflection on features of the NOS. An alternative approach is to engage learners in learning sequences that by design have embedded elements that engage learners in the practices that embrace the debates surrounding science as a way of knowing.

With respect to NOS itself, there is consensus that all of the seven tenets are inadequate, but very little consensus on better formulations, or even what is possible. One divide among our participants concerned the demarcation of scientific inquiry from non-scientific. Some participants suggested that scientific inquiry involves mechanistic explanations. This is clearly too narrow as magnetism and gravitation are not mechanical. Another suggestion was that scientific explanations are causal. This suggestion has two problems; one is that it seems to rule out statistical explanations that are not necessarily causal. The second is that two centuries of debate over the nature of causation in philosophy have produced no consensus on what constitutes causation. Another suggestion was that scientific explanations/hypotheses are *testable*. While this seems right in spirit, the attempts by philosophers to make this concept precise have also consistently failed. Another group of participants argued that the distinction between scientific and non-scientific hypotheses was real, but was not a matter for which we can formulate explicit rules. For them, the only way to understand the distinction is to be deeply embedded in the social practices of science and to have personal experiences of many examples.

The implication for school science is that knowledge of scientific principles and lawlike statements may be an important element in the development of values and criteria for distinguishing science claims and developing demarcation capacities; e.g., distinguishing science from pseudoscience. Adopting an enhanced scientific method framework based on supplements to the *7 tenets* has implications for the design of curriculum, instruction, and assessment models as well as for the models of teacher professional development. Critically important will be the need to bring about a focus on core components of school science, components that will serve as contexts that facilitate the cognitive activities and dialogical processes embedded in doing science. The next sections respectively examine the issues of curriculum development and teacher training development.

Immersion Units

Science distinguishes itself from other ways of knowing by appealing to evidence that is deemed objective by its practitioners and then using the evidence to put forth testable explanations. Scientific ideas and information are rooted in evidence and guided by our best-reasoned beliefs in the form of the scientific models and theories that frame investigations and inquiries. All elements of science - questions, methods, evidence and explanations - are open to scrutiny, examination, justification and verification. *Inquiry and the National Science Education Standards* (National Research Council, 2000) identify 5 essential features of classroom inquiry that are presented in Figure 1.

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- Learners are engaged by scientifically oriented questions.
- Learners give priority to **evidence**, which allows them to develop and evaluate explanations that address scientifically oriented questions.
- Learners formulate **explanations** from evidence to address scientifically oriented questions.
- Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
- Learners communicate and justify their proposed explanations.

Figure 1 – *Essential Features of Classroom Inquiry*

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The bold emphasis on evidence and explanation appears in the original. Science, at its core, is about acquiring data and then transforming that data first into evidence and then into explanations.

Preparation for making scientific discoveries and engaging in scientific inquiry is linked to students' opportunities to examine (1) the development or acquisition of the data and (2) the unfolding or transformations of data across the evidence-explanation (EE) continuum (Duschl, 2004). The dialogical strategy is to allow students to make and report judgments, reasons and decisions during 3 critical transformations in the E-E continuum. One is selecting data to become evidence. Two is analyzing evidence to generate models and/or locate patterns of evidence. Three is locating or otherwise determining the scientific explanations that account for the models and patterns of evidence. The advantage of the transformation approach resides in the opportunities for students to engage in, and importantly for teachers to monitor, the cognitive, epistemic and social practices of doing science.

Discussions at the conference led to the suggestion that in addition to the five essential features of inquiry in Figure 1, we would add that learners also be given opportunities to engage in the following dialogical processes:

- Respond to criticisms from others
- Formulate appropriate criticisms of others
- Engage in criticism of own explanations
- Reflect on alternative explanations and not have a unique resolution

An appeal of the E-E continuum as an instructional framework for guiding the design of curriculum, instruction and assessment models is that it reduces the expansive coverage and rapid pace of instruction so common in today's schools. A consensus point-of-view is that focusing school science on the 'big ideas' provides opportunities that allow learners to put knowledge to use and engage in important dialogical discourse processes that support learning and reasoning. Knowledge-in-use discourse strategies and literacy practices enable learning and reasoning to get beyond conceptual learning goals alone and facilitate development of important epistemic and social dimensions of scientific inquiry; e.g., arguing, modeling, explaining, questioning, valuating, representing, among others. (Norris, 2005; Bell, 2005)

A consensus view from the conference is the need for more research on the design and implementation of learning progressions. Project-based science, problem-based science, and full-inquiry science represent types of *immersion units* that embed within them extended instructional sequence opportunities to engage students in conceptual, epistemic and social dimensions of science learning and reasoning. The move to extended instructional sequences is motivated by cognitive sciences research on learning progressions (Catley, Lehrer & Reiser, 2004; Smith, Wiser, Anderson, Krajick & Coppola, 2004). This research is shaping thinking about the character, composition and nature of school science in terms of 3 questions posed at the conference:

1. What are the origins of the forms of scientific thinking?
2. Where does it go?
3. What are the supports that produce change in thinking?

According to Schauble (2005), we have good research on Question 1 but very little on 2 or 3. The implications of such research for the design of science education programs and for the professional development of teachers who implement the programs are significant. Answers to these questions will fundamentally change our images of school science. And, herein, as well, lies a significant tension for the design of science education programs of study.

On the one hand, the institutional culture of public education is severely constrained by economical, ideological and pedagogical conditions. Such constraints have the effect of promoting certain forms of curriculum, instruction, and assessment practices while denying others on the basis of cost effectiveness; e.g., professional development for K-12 teachers. On the other hand, research on learning and research on science learning are contributing to a richer understanding of the classroom contexts and conditions that promote scientific reasoning and understanding. Do we fit the research on learning into the instructional culture of schools or do we change the culture of schools to accommodate the learning research. There are significant policy and practice issues that come to the table.

Research shows that prevailing models of science teaching are lesson based rather than unit based, emphasize concept learning rather than knowledge system learning, and focus inquiry lessons on completing experiments rather than on testing and revising explanatory models. Science learning is partitioned into discrete units that contribute neither to the development of scientific knowledge systems nor to the development of cognitive, epistemic and social practices that undergird the evaluation of such systems. Recall, the list of cognitive activities in the Background section of the paper.

We need to develop carefully crafted instructional sequences that by design embed opportunities to engage learners in systems thinking and inquiry practices. The unfolding of data and evidence takes time and is another reason why effective inquiry units are longer in length. By pausing instruction to allow students to discuss and debate what they know, what they believe and what evidence they have to support their ideas, their thinking is made visible thus enabling the monitoring and assessment of the communication of information and of the thinking.

We must assist learners with the development of dialogical processes for both the construction **and** the evaluation of knowledge claims. Thus, by design, students are given extended opportunities to explore and critique the relationships between evidence and explanation. To this end, a consensus recommendation is to situate inquiry into longer thematic instructional sequences, where the theme is defined not by the conceptual structures of scientific content alone. Rather, the instructional sequence is designed to support acquisition and evaluation of evidence, as well as discourse, cognitive and reasoning skills that promote dialogical discourse processes.

The commitment here is to curriculum frameworks that promote extended instructional sequences around 'big ideas', unifying themes and principles of science rather than partial single lesson instructional sequences on discrete concepts, processes or skills. Typically, we are looking at units that are 2-4 weeks in length, but there are emerging perspectives that for some science knowledge systems and practices months and perhaps years need to be given to the learning, reasoning, and understanding tasks (c.f., Catley et al 2004; Smith et al 2004). The extended time is needed to make room for student conversations and representations of reasoning that, in turn, make possible engagement in inquiry employing the enhanced scientific method and cognitive development. Furthermore, in order to support learning, the immersion units typically contain tasks that help make students thinking visible and thus intentionally embed into the instructional sequence activities that facilitate feedback on the conceptual, cognitive, epistemic, and social goals of the unit:

- Developing scientific reasoning
- Communicating scientific ideas,
- Assessing the epistemic status of scientific claims.

Teacher Professional Development

In addition to cognitive constraints outlined in the previous sections, there are practical constraints that bear on suggestions for adopting an enhanced scientific method in school science. Principally, there are the constraints imposed by the knowledge and beliefs of classroom teachers. Two approaches with regard to teacher knowledge and school science prevail: (1) develop curricula to safeguard against lacunae of teacher knowledge; (2) develop curricula that embed conceptual/cognitive, epistemic, and social frameworks and that requires teachers' to develop expertise with implementing dialogical approaches to teaching. Kit-based science materials offered to K-8 science programs represents the first approach. Immersion unit and learning progression developmental programs described in the previous section and in Duschl (2004) and Edelson (2005) represent the second.

Research on students' epistemological reasoning about inquiry in science Driver, Leach, Millar & Scott, (1994) developed a three level framework for evaluating epistemological reasoning about science. The lowest level is phenomenon based reasong, the second is "relation-based" reasoning and the third is "model-based" reasoning. They found that students have a strong bias for H-D experiment-driven notions of doing science grounded in a strong reliance on sense-perception as the most reliable evidence, the least sophisticated orientation in the framework, below 'relation-based reasoning' and 'model-based reasoning'. What makes this finding for college students so surprising is that their subjects had completed 20+ college level science courses!

Research on beginning teachers' images of the nature of scientific investigations found that they are also functioning at or below the lowest epistemological reasoning level.   The beginning teachers' folk theory of doing science is strongly grounded in the standard notion of the scientific method and devoid of any references to the epistemic frameworks of science: claims, arguments, alternative explanations, models, etc. When asked to design an investigation, the beginning teachers based their questions on topics of personal interest and things that were doable or novel rather than on extant scientific models. (Windschitl, 2004, 2005) We need to reform more than just K-12 science education programs. The enhanced scientific method should be part of the college science courses taken by beginning teachers.   Opportunities to engage in 'immersion unit' type science learning should be a part of science teacher education programs.

Teaching the dialogic processes of science requires teachers capable of engaging learners in the activities listed in Table 1. New models of school science and of children's science learning rquire new models of teacher professional development. There is agreat deal of research to be done, and there are significant challenes as well in the face of alternative certification programs that allow school districts to hire unqualified science teachers.

Summary

The consensus of the conference participants suggests two main recommendations: (1) we need to consider a new sense of school science, particularly in the early grade levels, and (2) we need to adopt an enhanced model of what characterizes the scientific method in schools, colleges and universities. We have discussed specific 'school science' implications based on modifications for each of the *7 tenets* that suggest the adoption of dialogical processes that go beyond conceptual learning and extend to epistemic and social frameworks. The contexts for implementing this cluster of frameworks requires new models of curriculum, instruction, and assessment, some of which are beginning to appear in the literature. A consensus opinion from the conference was to explore the role of immersion units in school science with careful attention to domain specific learning progressions.

The constraints on implementing the two recommendations are multiple but we have highlight (1) the cognitive demands placed on learners and teachers during engagement with our elaborated sense of inquiry activities embedded in immersion units and

(2) the implications for beginning science teacher preparation programs.

Another implication for contemporary science education practice concerns the debate about how best to develop learners' understanding of the nature of science. Our review of the *7 tenets* and endorsement of immersion unit approaches to the teaching of scientific inquiry suggest that an alternative approach to generic lists is to engage learners in extended learning sequences that by design have embedded elements that engage learners in the practices that embrace the debates surrounding science as a way of knowing.

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Table 1. The Learner/Teacher Continua

Learner engages in scientifically oriented questions				Teacher engages in scientifically oriented questions
Learner gives priority to evidence in responding to questions				Teacher gives priority to evidence in responding to questions
Learner formulates explanations from evidence				Teacher formulates explanations from evidence
Learner connects explanations to scientific knowledge				Teacher connects explanations to scientific knowledge
Learner communicates and justifies explanations				Teacher communicates and justifies explanations
Learner responds appropriately to criticism of explanations				Teacher responds appropriately to criticism of explanations
Learner can formulate appropriate criticism of alternative explanations				Teacher can formulate appropriate criticism of alternative explanations
Learner can criticize their own explanations				Teacher can criticize their own explanations
Learner can construct tests to discriminate between explanations				Teacher constructs tests to discriminate between explanations
Learner can reflect on the fact that sometimes there are multiple explanations and no currently definitive answer				Teacher discusses the fact that sometimes there are multiple explanations and no currently definitive answer.

Appendix A
NSF Conference Participants

Day 1
Inquiry: The Child as Scientist
William Brewer, University of Illinois
In What Sense Can The Child Be Considered to be a "Little Scientist"?
Commentator: Leona Schauble, Vanderbilt University

Inquiry: How Science Works
Nancy Nersessian, Georgia Tech University
How science works
Commentator: Fouad Abd-El-Khalick, University of Illinois

Inquiry: Knowledge as Social Processes
Miriam Solomon, Temple University
Social Epistemology of Science
Commentator: Nancy Brickhouse, University of Delaware

Inquiry: Conceptual Change and Constructivism
Greg Kelly, Penn State University
Inquiry, Activity, and Epistemic Practice
Commentator: John Rudolph, University of Wisconsin

Panel A — *Philosophical Issues and Next Steps for Research*
Richard Grandy (Chair), Rice University; Harvey Siegel, University of Miami; Stephen Stich, Rutgers University; Helen Longino, University of Minnesota

Day 2
Inquiry: Epistemic Practices in Classrooms
David Hammer, University of Maryland, (with R. Russ, J. Mikeska & R. Scherr)
Identifying Inquiry and Conceptualizing Abilities
Commentator: William Sandoval, UCLA

Inquiry: Engineering the Design of Learning Environments
Dan Edelson, Northwestern University
Engineering Pedagogical Reform: A Case Study of Technology Supported Inquiry
Commentator: Janice Bordeaux, Rice University

Inquiry: Learning to use Data, Models and Explanations
Clark Chinn, Rutgers University and Ala Samarapungavan, Purdue University
Learning to Use Scientific Models: Multiple Dimensions of Conceptual Change
Commentator: Joe Krajcik, University of Michigan

Inquiry: Literacy Practices and Science Communication
Stephen Norris, University of Alberta (With Linda Phillips, University of Alberta)
Reading as Inquiry
Commentator: Philip Bell, University of Washington

Panel B- Policy, Practice and Next Steps for Educational Research
Drew Gitomer (Chair), University of Chicago, Cindy Hmelo-Silver, Rutgers University; Eugenia Etkina, Rutgers University; Mark Windschitl, University of Washington

Appendix B

Philosophical Debates about the Nature of Science

(from Eflin et al, 1999)

Unity of Science versus Disunity of Science. This debate bears directly on the NOS tenets because some philosophers of science believe that different sciences have very little in common. Some advocates of the disunity of science believe that there simply is no "nature" of science; some believe that there is nonetheless a family resemblance. There are a variety of reasons available (metaphysical, epistemological, and scientific) for holding these views which we have not discussed, most of which bear on the NOS issues.

Demarcation. The task of demarcating science from other forms of inquiry was an important component of philosophy of science of the 1930s and 1940s (that is, of logical positivism or logical empiricism). In the wake of its decline, most philosophers believe that it is impossible to formulate criteria that demarcate science and nonscience. This question is closely related to that of the unity and disunity of science. Some believe that theories and practices can be identified as more or less scientific, while a few, particularly those inspired by developments in literary theory (and all things French), would maintain that there is no distinction at all between science and nonscience. The view that there is no genuine distinction tends also to be championed by some sociologists of science, particularly social constructionists. On the other hand, philosophers active in debates about creationism and a constitutional (as opposed to philosophical) separation of science and religion argue that some ways to demarcate science from nonscience, such as Popperian demarcation, remain workable and important.

Realism versus Instrumentalism. Debate about realism was mentioned above and takes different forms in different branches of philosophy of science. Usually, it concerns the metaphysical question of whether theoretically posited entities (such as quarks in physics, or economies in social science, or species in biology) actually exist objectively and behave according to the theories or laws that describe them. A realist in one of these domains believes such entities do exist, often on the grounds that theories about them would otherwise not be successful. Instrumentalists, or antirealists, believe instead either that such entities do not exist or that the success of theories does not reliably prove that they exist. They regard theories and theoretical entities as tools or instruments that nonetheless help us to understand and manipulate the world. Some philosophers are realists about one scientific domain, but antirealists about others. Furthermore, some philosophers classify themselves neither as realists or antirealists, but argue instead that the realism debate is sterile, or even meaningless.

Rationalism versus Historicism. Largely in response to Thomas Kuhn's influential work (1974, 1970), in which the history of science is portrayed as a sequence of sometimes mutually contradictory paradigms or worldviews, the issue known as "theory choice" came to dominate philosophy of science. Viewed one way, the central question is whether scientists rationally and deliberately choose which theories they believe are best (rationalism) or whether, as Kuhn seemed to imply, their allegiances are determined by historical and social forces manifest in their training and in intellectual fashions (historicism). Kuhn even likened changes of scientific belief to religious "conversion experiences" (Kuhn, 1970, pp. 151 and 204) and thereby challenged critics to specify precisely in what scientific rationality consists. Most who took up the challenge (Lakatos, 1978; Laudan, 1984, 1977) agreed with Kuhn that scientific change was sometimes radical and revolutionary, but aimed to show that the process was still either rational or progressive in certain ways. Others attempted to apply Bayes' theorem of rational choice to theory choice in science. This debate, however, has largely fallen from philosophical interest in recent years. Almost all philosophers (but not all historians or sociologists) now eschew radical historicism.

Practice and Experiment versus Theory. This debate involves the question: Is science a body of knowledge or is it something more inclusive, such as a way of life or a body of practical techniques? Several philosophers and historians in the 1980s argued that to fully understand the NOS, one must take into account the way scientists do experiments, the ways they organize and structure their laboratories, and the ways they operate in political, economic, and cultural networks. Most philosophers would agree that these are important for understanding science. One important area of disagreement, however, is whether scientific knowledge is merely contained within scientific practice or scientific culture on the one hand, or whether it is inextricably formed and maintained by it.

Feminist Philosophy of Science. Historically, women have been excluded from science.
How has this shaped scientific theory or scientific practice? Feminist authors ask: Whose knowledge is this? Whose experiences provide the evidence? Who decides what the scientific goals are? Feminists approach the goals of science as multilayered and context dependent, frequently claiming that there is no unconditioned subject position. Rather, knowledge results from social interactions among members of a community and between them and the purported objects of knowledge. Some feminists claim that male-centered science results in bias or problematic and unquestioned presuppositions. Other questions include: Are there distinct feminist research methods? If so, are they appropriate for the natural sciences? What would a feminist science look like? Most feminists claim that taking these concerns into account will result in better science. Some claim, more strongly, a different science will result.