

Reconsidering the Character and Role of Inquiry in School Science: Framing the Debates

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Introduction

The purpose of this paper is to provide a structure for discussion of science education with the goal of synthesizing developments in

- (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.

Taken together 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 there is general agreement that important changes have taken place, it is less clear where there is consensus on the new directions and where there is not. Furthermore, it is not clear yet which of the areas of dissensus represent lacuna relevant to science education and which are irrelevant for science education, however central they may be to philosophy of science, psychology of science, history of science, or any other area of science studies. Our goal in this conference is to determine areas of consensus and areas where we lack consensus, and among the latter to identify which areas are crucial for the further development of science education and which are not.

Since the first NSF funded era of science education reform in the 1960s and 1970s, we see a shift from science as experimentation to science as explanation/model building and revision; from learning as a passive individualistic process to learning as an active individual **and** social process; from science teaching focusing on the management of learners' behaviors and "hands-on" materials to science teaching focusing on the management of learners' ideas, access to information, and interactions among learners. Some of the shifts have been motivated by new technological development but new theories about learning have contributed too.

One important change that has significant implications for the role of inquiry in school science concerns the realm of scientific observations. Over the last 100 years new technologies and new scientific theories have modified the nature of scientific observation from an enterprise dominated by *sense perception*, aided or unaided, to a *theory-driven* enterprise. We now know that what we see is influenced by what we know and how we "look"; scientific theories are inextricably involved in the design and interpretation of experimental methods.

New technologies and learning theories also have effected how we monitor, diagnose and nurture learning. Scientific databases like Geographical Information Systems (GIS) make it possible to engage in rich scientific inquiry without engaging in hands-on science involving the collection of data. Instead, the data are provided and the inquiry begins with the selection of information for analysis. This is one example of how science education has shifted from management of materials for collecting data to management of information for scrutinizing databases. Such a shift has implications regarding the manner in which interactions with phenomenon are designed and included

in science lessons for all grade levels. Information in the guise of data, evidence, models and explanations represents, in an important sense, the new materials for school classrooms and laboratories. Taken together these developments in technologies and theories have implications for how we conceptualize the design and delivery of science curriculum materials for purposes of supporting students' learning as well as teachers' assessments for promoting learning.

The use of computer-supported instrumentation, information systems, data analysis techniques and scientific inquiry practices in general, has created a problem. The language of science in schools and in the media has not kept pace with the language of scientific practice -- a practice that is decreasingly about experiments and increasingly about data and data modeling. In brief, one could argue that causal explanations grounded in control of variable experiments have largely been replaced by statistical/probabilistic explanations grounded in modeling experiments. The language of science in each experimental context is different. A reconsideration of the role of inquiry in school science must address this language gap and herein lays the importance of promoting scientific discourse practices. Examples of newly designed inquiry curriculum sequences that are striving to address the language gap include the LETUS program at Northwestern, the Learning By Design program at Georgia Tech, the SCOPE program at Berkeley and University of Washington, the WISE program at Berkeley, and the MUSE program at Wisconsin, among others.

These approaches adopt a model of science instruction that situates learning within design, problem or project contexts. The design, problem, or project based immersion units represent 4-6 week long lesson sequences that are situated within a compelling context to motivate students and to advance rigorous learning. Furthermore, in order to support learning, the immersion units typically contain tasks that help make students thinking visible and thus provide teachers with valuable insights about how to give feedback to students in each of the three goal domains

- promoting the communication of scientific ideas,
- developing scientific reasoning
- developing the ability to assess the epistemic status that can be attached to scientific claims.

The goal is to assist learners with both the construction and the evaluation of knowledge claims. Thus, by design, students are given extended opportunities to explore the relationships between evidence and explanation. To this end, inquiries are situated into longer thematic instructional sequences, where the theme is defined not by the conceptual structures of scientific content alone. Rather, the sequence of inquiries is designed to support acquisition and evaluation of evidence, as well as language and reasoning skills that promote progress toward a meaningful inquiry goal; e.g., the design, problem or project. The shift from a content/process focus of science education to an evidence/explanation focus has significant implications about the role of inquiry in school science.

The lesson sequence approach, referred to as full-inquiry or immersion units, stands in stark opposition to single lesson approaches that partition concepts and processes. Osborne and Freyberg (1985) report that students' understandings of the goals of lessons do not match teacher's goals for the same lessons. When students do not understand the goals of inquiry, negative consequences for student learning occur (Schauble, Glaser, Duschl, Schulz & John, 1995). Unfortunately, the single science lesson approach is the dominant practice found in schools. By situating science instruction and learning within a design-based, problem-based, or project-based context, to which members of the class have both individual and group responsibilities, a very different classroom learning environment develops. Specifically, the design of thematic instructional sequences allow us to approach closer to an understanding of the developmental landscapes located within domains of science learning; landscapes that do not presuppose a single developmental trajectory or path but do require a clear understanding of the conceptual, epistemic and social developmental goals within a unit of science instruction.

When we synthesize the learning sciences research (c.f., Bransford, Brown & Cocking, 2000; Pellegrino, Churkowsky & Glaser, 2002), the science studies research (c.f., Giere, 1988; Hull, 1988; Longino, 2002; Nersessian, 1999) and science education research (cf. Millar, Leach & Osborne, 2001; Minstrel & Van Zee, 2001) we learn that : (1) The incorporation and assessment of scientific inquiry 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 inquiry learning and assessment improve through the establishment of:

- Learning environments that promote **student centered 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, and
- Teacher designed assessment practices that **monitor learning and provide feedback** on thinking and learning in each of the three domains.

Full inquiry or immersion units promote the meaningful learning of difficult scientific concepts, the development of scientific thinking and reasoning, the development of epistemological criteria essential for evaluating the status of scientific claims and the development of social skills concerning the communication and representation of scientific ideas and information. Providing students with opportunities to engage with natural phenomenon and to link evidence to explanations is vital. In the sections to follow, we will examine, how research from science studies, the learning sciences, and educational research each argues for the reconceptualization and reorganization of inquiry instruction.

Changing Images of Inquiry

Over the last 50 years, science education in the USA has been a strong focus of attention. Following on from World War II, steps were taken to sustain the scientific superiority that contributed to winning the war. New technologies and new frontiers of science defined post-war America. Policy makers agreed that in order to keep our technological

and scientific edge science education in our pre-college schools and classrooms needed changes that would modernize both what was taught and how it was taught.

The task of overhauling high school science programs initially fell to the same scientists who contributed to our war effort (Rudolph, 2002; Duschl 1990). The goal was to establish a curriculum that would develop in learners the capacity to think like a scientist and prepare for a career in science, mathematics and engineering. Thus, not surprisingly, the initial NSF-funded science curriculum (PSSC, BSCS, CHEMSTUDY) had a ‘science for scientists’ focus of instruction. Embedded within the ‘science for scientists’ approach was a commitment that students should be provided opportunities to engage with phenomena; that is to probe the natural world and conduct inquiries that would reveal the patterns of nature and the guiding conceptions of science. The goal was to downsize the role of the textbook in science teaching and elevate the role of investigative and laboratory experiences in science classrooms. That is, according to Joseph Schwab (1962), first director of BSCS, science education should be designed so that learning is an ‘enquiry into enquiry’ and not a rhetoric of conclusions, e.g., teaching what we know.

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 time 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:

- 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 NSES 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 where science education has not kept pace with developments in science. That is, 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.

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. 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).

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.

Looking back there are several trends in science education that have altered our images of the role of the inquiry in science education:

- From a goal of providing science education for scientists, to providing science education for all.
- From an image of science education as what we know, to science education as teaching science as a way knowing.
- From an image of science education that emphasizes content and process goals to science education that stresses goals examining the relation between evidence and explanations.

- From an emphasis on individual science lessons that demonstrate concepts, to science lesson sequences that promote reasoning with and about concepts.
- From the study of science topics that examine current scientific thinking without regard for social context, to the study of science topics in social contexts.
- From a view of science that emphasizes observation and experimentation, to a view that stresses theory and model building and revision.
- From a view of scientific evidence principally derived from sense- perception (either direct or augmented) to a view that evidence is obtained from theory-driven observations.

The implications for teaching inquiry in school science are significant since these changes raise questions about

- (1) the amount of time allocated to interactions with basic scientific phenomena;
- (2) the depth and breadth of experiences learners bring with them to the science classroom; and
- (3) the kind of phenomena and experiences that stimulate science learning.

As stated above, the 1960s NSF sponsored revolution in science education focused on a science for scientists approach. Twenty years later after an enormous infusion of scientific knowledge into all walks of life, arguments for a science for all approach to science education began to emerge. We now see scientific knowledge as indispensable for participation in the workplace and in a modern democracy. However, the science education community has been slow to embrace new philosophical, psychological and pedagogical models that can inform the design of curriculum, instruction, and assessment frameworks that, in turn, inform the place of inquiry in science education.

Changing Images of Science in Science Studies in the 20th Century

It is well beyond the scope of this paper to provide a comprehensive review of developments in the various areas of science studies; the interested reader can find useful summaries in Godfrey-Smith (2003), Duschl (1990, 1994) and Matthews (1994). In very broad brushstrokes, 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. Some of the major figures in the movement were Rudolf Carnap, Carl G. Hempel, Ernest Nagel, and Hans Reichenbach. In the 1950s and 60s, various writers questioned many of the fundamental assumptions of logical positivism and argued for the relevance of historical and psychological factors in understanding science. Thomas S. Kuhn is the best known of the figures in this movement, but there were numerous others, including Paul Feyerabend, (1993) Norwood Russell Hanson (1958), Mary Hesse (1966), and Stephen Toulmin (1959, 1961). Kuhn (1962/1996) 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. One important aspect of Kuhn's work was the distinction between revolutionary and normal science. Revolutionary science involves significant conceptual changes, while normal science consists of "puzzle solving", of making nature fit into the boxes specified by the disciplinary matrix.

In this view of science, theories still played a central role, but they shared the stage with other elements of science, including a social dimension. 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 in philosophy of science can be seen as filling in some of the gaps left by Kuhn's demolition of the basic tenets of logical positivism. 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.

One can summarize developments 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 view of science emerged out of the early 20th century activities of the Vienna Circle and related movements in Berlin and Poland. Peano, Frege, Russell and Whitehead had apparently shown that all of mathematics could be reduced to a single syntactically formulated axiomatic system¹. The commitment among a group of natural philosophers (e.g., Mach, Carnap, Hempel, Reichenbach) was that science like mathematics should be grounded in the new symbolic logic. The enterprise gave birth to the movements called logical positivism or logical empiricism and 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 which accrued to established knowledge. How knowledge was discovered was not the philosophical agenda, only the justification of knowledge was important. This early 20th century perspective is referred to as the ‘received view’ of philosophy of science.

This 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.

¹ Kurt Godel, a member of the Vienna Circle, demonstrated in 1931 that there could not be a complete axiomatization of mathematics--this discovery seems to have had less impact on the development of logical empiricism than, with hindsight, it should have.

It is important for our purposes 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.

Logical Positivism

We find it helpful to identify *seven main tenets of philosophy of science that* underly logical positivism:

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 s
5. Scientific development is cumulatively progressive.
6. Different scientific frameworks are commensurable.
7. Scientific theories can most usefully be thought of as sets of sentences in a formal language.

Our discussion of these tenets will necessarily be brief and in many cases simplify complicated issues. For more detailed discussions, see; (Hempel 1970, Suppe 1977, and Friedman 1999) for further discussions.

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. A statement about the mass of an object in the range of 20 grams to 2000 kilograms would be an observation statement, but a statement about the mass of a star or of an electron

would be theoretical. (Hempel, 1966) One of the most important external critics was Norwood Russell Hanson with his book *Patterns of Discovery*. This has led to the recognition that our ordinary perceptual language is theory laden, that we talk about the red shift of stars or the solubility of sugar, and this has led gradually to the recognition that a better description of what we are doing is creating models of data. This began in the 60s but has been accelerated with the development of computers so that much more powerful modeling techniques are now available and computational power is increased unimaginably. Modeling efforts such as the human genome project or efforts to understand global climate changes were inconceivable in 1970. New measurement techniques, indeed measurement of quantities that were not suspected, such as the geomagnetic patterns in the ocean floor, have led to the creation of new forms of data as well. This in turn has led to large databases which are available for classroom use.

Logical positivists were slow to recognize the shift in what counts as observational, which is not a matter of grammar but evolves historically as science changes. 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 create images of individual atoms and we can manipulate them individually.

Tenet 2, the belief in inductive logic was important as part of the conception of scientific rationality. Based on the success in developing a deductive logic that was adequate for almost all mathematical purposes, the logical 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. 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. For example, the law that all copper melts at temperature t , would be represented in logical notation as $(\forall x)(Cx \supset Mxt)$ where C represents the property of being copper and M the relation that holds if x melts at temperature t . The formal sentence is transliterated into English as: "For all values of x , if x is copper, then x melts at temperature t ." Fundamental problems beset the positivist project and they did not progress beyond very elementary examples in their discussions of confirmation and theory evaluation. (See Hempel, 1943, for the early version of the program, and Hempel 1988 for a postmortem discussion of the successes and (mostly) failures of the program.) The problem with Tenet 3 is not that it postulates a distinction between the context of discovery, the situation in which a theory is first discovered, and the context of justification, the presentation of the theory in its final axiomatized form, but that these were seen as exhausting the process of theory development.. 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 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 focus 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. Some people describe this feature of the scientific process by saying that scientific claims are tentative; we prefer to say that science and scientists are *responsive*, thus avoiding the connotation that tentative claims are unsupported by evidence or scientific reasoning.

(Tenets 4-7 will be discussed later in the contexts in which they come into question instead of being presupposed.)

One of the most striking points that Kuhn made in *Structure* was that science textbooks are a monological presentation of *ex post facto* evidence for current theories

and entirely suppress the dialogues concerning alternative conceptions and apparent evidence against the current theory. The more sophisticated and looser contemporary construal of the connection between theory and data recognizes that, when we have an apparent conflict between theory and data, we sometimes reject the theory. How and why to revise the theory is a complicated epistemic matter and since there is no algorithm for theory change, the changes almost always require dialogic justification within the context of the relevant social structure of expert scientists.

Sometimes, however, we reject the data, and again, contra logical positivism, since there is no privileged observation language and no theory choice algorithm, this decision is a matter of judgment. And sometimes we reject both theory and data. A historical example is Tycho Brahe who rejected both the Copernican and Ptolemaic theories of the solar system and created new instruments to make better observations. He hoped that his better observational data would support his own unique compromise which maintained the earth in the center of the universe, but which had all of the other planets (except the moon) circling the sun which circled the earth. Instead, his data provided evidence which led Kepler to his three laws of planetary motion, and moved one step further toward the Newtonian conclusion of the Copernican revolution. (T S. Kuhn, 1957)

One important question for our context is at what stage of science education we introduce these complications about data revision, theory revision and their interaction. Like logical positivism, science education which teaches final theory has no place for these essential elements of the development of science. While knowledge of final (or at least current) theory is the main goal of science education for scientists, it should not be for science education for well-informed citizens.

The 3rd tenet, the dichotomy between context of discovery and context of justification, involves the contingent psychological and historical situation in which a theory was first conceived or discovered and contrasts it with the context in which a theory, presented in a formal language according to Tenet 2 was evaluated/justified for acceptability. Given this either/or perspective of end-point theory evaluation, it is significant to note there was no recognition of the important intermediary processes between these two stages of scientific development in the growth of scientific

knowledge. In particular, we wish to stress the importance of the dialogic processes that shape and focus evidence as well as explanatory frameworks. Such processes are eminently, and simultaneously, cognitive, epistemic, and social in constitution and are critical to the design of science learning environments.

Conceptual Change

In the first edition of *Structure*, Kuhn defined two kinds of scientific development in terms of *paradigms*. Normal science involves the articulation and refinement of a paradigm that is shared by the relevant scientific community; in revolutionary scientific change, one paradigm is rejected and another takes its place. One reason for the widespread influence of the book outside of the community of philosophers and historians was that the conception of a group or community guided by a paradigm seemed to have explanatory value in many settings. This use of the term has become firmly entrenched as a standard expression in English and appears in cartoons and business management courses although most of its contemporary users have no notion of its source.

However useful the term "paradigm" has proven in the general culture, it was the cause of considerable criticism in the reception of the book because critical readers perceived that he was using the term very variously and loosely. One critic (Masterman, 1974) taxonomized twenty-two distinguishable senses of the term in *Structure*. Kuhn disagreed with the precise count, but saw that clarification was required. Many of the criticisms were aired at two important conferences that focused heavily on his work. The first was held in London in 1965 and the second in Champaign IL in 1969. The proceedings of these were eventually published as *Criticism and the Growth of Knowledge* (ed. Lakatos and Musgrave, 1970) and *The Structure of Scientific Theories* (Suppe, 1977). As a result of these influences and further reflection, in the "Postscript" to the second edition of *Structure* in 1970 Kuhn expressed a desire to replace the term "paradigm" with two new terms, "exemplar" and "disciplinary matrix", which he believed expressed the two main distinct uses he had made of "paradigm." Much of the confusion regarding Kuhn's position is also caused by the fact that Kuhn never rewrote

Structure clarifying which sense of 'paradigm' he intended in each context, he merely added the postscript. Thus, first time readers would first pass through the original representations of paradigms guiding conceptual change, and most likely not realizing the radical revisions presented in the postscript. Qualifications on the meaning of paradigm as that found in the postscript of *Structure* are also expressed in his contributions to the London and Illinois conferences.

Exemplars represent one new meaning of "paradigm" (and the final element of a disciplinary matrix) and Kuhn emphasizes that these are *concrete* examples of problem solutions. One of the most crucial points in his emphasis on exemplars is that they give guidance to future research *by example*, not by incorporating rules or explicit method. A scientific field or specialty is given its coherence partly by these shared examples, but it is given its diversity of approaches by the possibility of researchers interpreting those examples somewhat differently from one another. Researchers can all agree that they want to do for their field what Newton did for his, but they may disagree fairly radically about what that was, and therefore on what they intend to achieve. Some of the confusion in interpreting *Structure* was due to the fact that one sense of paradigms, exemplars, are an element of the other's sense, disciplinary matrices.

In a *disciplinary matrix* Kuhn intends to include at least seven elements: equations or other symbolic representations, instruments, standards of accuracy and experimental repeatability, metaphysical assumptions, values, and the domain of inquiry. The domain of inquiry, in turn, includes the problems which workers in the field regard as relevant but unsolved and the workers' shared exemplars, the problem solutions which are set forth as examples of good solutions of important problems. With the modifications provided by the disciplinary matrix, the growth of scientific knowledge was conceptualized as a problem solving activity. A philosophical concern arose though concerning the direction of growth and the factors that influenced growth. One issue confronting philosophers was to explain how growth, conceptual change and problem solving was or could remain a rational and objective process. That is, given two theories T1 and T2, how was one to determine if T2 was a legitimate choice over T1 and on what grounds (e.g., epistemological, political, social or otherwise). We take up this issue below in discussions of Lakatos and Laudan, two philosophers who attempted

to 'save the phenomenon' of sciences' image of being rational and objective. We extend the discussion as well in the next section of model-based views of the nature of science.

Kuhn's work gave a prominent place to both history of science and psychology, both of which were absent from the received view. In science studies, the recognition of the context of theory development provides a significant place for cognitive psychology in the study of science. Kuhn relied on Gestalt psychology, but since then the new post-behaviorist cognitive revolution has produced valuable studies on learning, concept acquisition and related themes.

One very important element for our purposes is that Kuhn recognized that a scientific community shared values and *examples/exemplars* as well as explicitly articulated elements such as equations. It is partly the tacit and somewhat variable construal of the values and exemplars that makes the community essential. Just as variation among genes within a species gene pool provides the material for further adaptation, the variation in the scientific community is a valuable resource for further development of that community and the growth of knowledge within the community.

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. This, together with his rejection of Tenet 2, (inductive logic) produced negative reactions from many philosophers. Including a social dimension was seen as threatening the objectivity and rationality of scientific development. His denial of Tenet 5, that scientific development is always cumulatively progressive, and his arguments against Tenet 6 that disciplinary matrices on different temporal sides of a revolutionary change are incommensurable also produced negative reactions. Some of this was because of misunderstanding of "incommensurability" which he took to mean that the competing matrices were not comparable in any rational way. Kuhn was using the term in the old Greek sense meaning that no "ratio" exactly captures the relation, though one can approximate it as closely as one likes. And his denial that science is always progressive also produced criticism and outrage. As Kuhn confessed in 1993

"To my dismay, ...my 'purple passages' led many readers of *Structure* to suppose that I was attempting to undermine the cognitive authority of science rather than to suggest a different view of its nature. And even for those who understood my intent, the book had little constructive to say about how the transition between stages comes about or what its cognitive significance can be. (Kuhn, 1993, 314)

Also of considerable significance in understanding the impact of Kuhn's work was the "strong programme" in sociology of science which saw Kuhn's work as showing that science is essentially a matter of power struggles and personalities and not a matter of evidence and explanation; objectivity and rationality. Kuhn strongly disagreed with these alleged consequences of his work, in fact countered by arguing:

Properly understood...incommensurability is far from being the threat to rational evaluation of truth claims that it has frequently seemed. Rather, ... its needed to defend notions like truth and knowledge from, for example, the excesses of postmodern movements like the strong program. (Kuhn, 1990, 91)

But because he was claimed as a progenitor by the strong programme many critics saw him as part of that movement. The assessment is complicated by the fact that while Kuhn rejects one aspect of Tenet 5, he accepts another. He believes that if we consider two scientific theories, one of which is a descendant of the other, we could tell which is the earlier and which the later by such criteria as comparative accuracy of predictions, number of problems solved, and degree of specialization. He comments that "For me, therefore, scientific development ... is unidirectional and irreversible. One scientific theory is not as good as another for doing what scientists normally do.(Kuhn, 1970, p 160).

However, while embracing increasing empirical adequacy, Kuhn denies that science is coming closer to a description of ultimate reality. He discusses philosophers who "Granting that neither theory of a historical pair is true ...seek a sense in which the

later is a better approximation to the truth. I believe nothing of that sort can be found. (160) (For further discussion of Kuhn's views on these matters, see Grandy 2003a)

A number of philosophers saw the merit in Kuhn's criticism of Tenets 1-3, but disagreed with his criticisms of Tenets 4-6 and proposed alternative frameworks. Thus a second important figure in the development of the conceptual change view of philosophy of science was Imre Lakatos. Lakatos was one of the critics of *Structure* who felt that Kuhn was misrepresenting science as less rational and objective than it actually was. "...in Kuhn's view scientific revolution is irrational, a matter for mob psychology. Lakatos agreed with Kuhn in rejecting Tenets 1 and 2, but insisted on 3 and remained sympathetic to the remainder. In order to provide what he saw as rational criteria for theory choice without Tenets 1 and 2, he introduced the terminology of research programmes and distinguished between negative and positive heuristics. (Lakatos, 1978) Negative heuristics signaled theory development that was deteriorating while positive heuristics represented theory development that was progressive. Among the positive heuristics are better solutions, or more accurate solutions to old problems, but more importantly the prediction of novel facts that are confirmed (*e.g., Mendeleev's prediction of elements in support of the periodic law; Huxley's prediction of two-toed horses in support of the theory of evolution, Tuzo Wilson's prediction of transform faults in support of the theory of plate tectonics*). Using that theoretical apparatus, Lakatos distinguished progressive and degenerative research programme trajectories.

A third significant figure was Larry Laudan who sought to represent the growth of scientific knowledge in terms of the progress being made among broad based communities of scientists which he called "research traditions". Laudan interpreted Kuhn as concluding that "scientific decision making is basically a political and propagandistic affair, in which prestige, power, age, and polemic decisively determine the outcome of the struggle between competing theories and theorists" (Laudan, 1977 p. 4). We disagree with that interpretation of Kuhn, interpreting him rather as rejecting a traditional conception of rationality and urging the philosophical and historical examination of the history of science to eke out a more realistic conception of rationality. (See Kuhn, 1977, 2000 and Hempel 1983a, 1983b for further discussion.)

Although we disagree with Laudan on this central issue of Kuhn interpretation, we believe that his distinction between empirical and conceptual problems is helpful, as too is his term “research tradition” and his characterization of when a research tradition is progressing. Empirical problems are matters of fitting descriptions to the world. Galileo’s search of the laws of falling bodies was an attack on an empirical problem, as was the problems involved in filling in the periodic table after Mendeleev had the basic insight. Mendeleev solved the conceptual problem of how to organize the elements—portraying them as a two dimensional array made evident important relationships that had been invisible using the older one dimensional array of elements. Thus, conceptual problems are those that arise when a theory or theoretical framework in one domain conflicts with theories from other cognate domains. Empirical problems represent the extent to which the theory or theoretical frameworks fits or accounts for object and material evidence. Copernican and Ptolemaic astronomy provided empirically equivalent predictions of the retrograde motions of the planets. However, the Copernican system provided a **principled** explanation of the retrograde motions while the Ptolemaic system had only an ad hoc adjustment to fit the empirical data.

Using the problem solving theoretical apparatus, Laudan (1977) attempted to characterize when a research tradition is progressing, and when it is not, in terms of increased problem solving ability in one or both of these areas. A research tradition progresses when it successfully solves conceptual and/or empirical problems. The research tradition developing Newton's theory of universal gravitation made continual empirical progress in early stages as new phenomena such as tides and comets were brought within the scope of the theory. It made empirical progress in later stages as new planets were postulated, and discovered, on the basis of the theory. On the other hand, critics of the theory, especially Cartesians in France, continued to point to the *conceptual* problem that the theory lacked any account of how gravity produced the effects it does. It was not conceptually progressive and was eventually superseded by general relativity.

Lakatos, Laudan and others sought to accommodate what they regarded as the important insights of Kuhn’s *Structure*, but *also tried* to restore a more familiar sense of rationality and progress. Kuhn disputed their claims and thought that the dialectical

social processes that take place in scientific communities constituted the best example of rationality. In any event, one of the lessons from science studies is that social processes such as peer review are essential to scientific objectivity, and thus for students to understand the processes of science we must introduce argumentation discourse in the classroom. And this should be situated in the context of improving and refining perspectives, theories, data, models and knowledge claims.

Returning to the theme of “the scientific method”, we can now recognize that the initial process of “observation” in Step 1 already involves many presuppositions about how the world works, that the choice of hypothesis will be guided, perhaps constrained, by the appropriate disciplinary matrix, that the deduction of consequences typically requires auxiliary assumptions, that the design of the experiment to make the subsequent observation possible depends on theoretical assumptions about intervening causes and the design and function of instruments, and finally that the evaluation of the fit between “observation” and “prediction” is less than clear-cut in many cases.

Having given up the logical positivist assumption that there is a unique algorithm for evaluating the fit between theory and data, and the assumption that there is a privileged unproblematic observation language, we recognize that the dialogic processes by which theory evaluation and data construction occur in the community are an indispensable part of the rational structure by which science unfolds. One central question is where in the trajectory of science education we should introduce these complications of simultaneous revision of theory and data. We know that six year olds come to the classroom with concepts, theories and belief in data. Can we already introduce some elements of the dialogic processes at that level?

Recent research on the persistence of false beliefs (Gilbert, 1991) (Gilbert et al 1993) indicates that the process of dispelling prior misconceptions is much more difficult than has been appreciated among advocates of conceptual change teaching methods. More investigation of the processes involved in the relevant contexts would be very helpful.

Model based science: Language, representation and communication²

² Some material in this section derives from (Grandy, 2003a))

Emphasis on understanding the relations between data, theories and naïve observation stems from the work of Kuhn, Hanson and others, but has only become a focus for philosophy of science in the last 20 or 30 years. Among the major contributors are Ackermann (1985), Bechtel(Bechtel & Richardson 1993), Cartwright (1983), Giere (1988,1999), Longino, (1990, 2002), Mayo (1996) and Fred Suppe (1989). Surely having an erroneous view of the nature of scientific theories was an impediment to science education, and having a correct one should be a boon. But we will see that reaping these benefits will probably require more consensus, or at least more discussion and clarification than we have achieved thus far. For a start, there is no generally agreed on name for the new view, unfortunately. It has been called “semantic, “structuralist, “model-theoretic, “set theoretic“, “non-statement” and more recently a favored term has been “model-based”. This may just be an issue of nomenclature, but it may also reflect some important uncertainty about details.

One of the most careful statements of the philosophers’ new views is probably Suppe's. His “nuanced sloganistic analysis” of the new view is that, “Scientific theories are causally-possible collections of state-transition models of data for which there is a representation theorem.” (Suppe 2000, p. S111) A representation theorem means that there is a mapping from measurable quantities of physical systems to the mathematical system in which the structure of relations among quantities is reflected by parallel relations among real numbers. Causally possible collections are those that are consistent with experiment and theory, while a 'state transition model' is a systematic description of how the states of the physical system change over time.

To take a simple example, if we are theorizing about cylinders rolling down an inclined plane, then the relevant physical quantities are the slope of the plane, the radius of the cylinder, distribution of mass in the cylinder , the location of the cylinder on the plane and its velocity. A state transition model would describe how later states of the cylinder are related to earlier states and the causally possible ones are those consistent with Newton's laws of motion and gravitation.

Developmental psychologists have also shown an interest in the new *model-based* view and used it in arguing for cognitive continuity between infant and adult science; i.e., children are fundamentally the same kind of reasoners as adults. The prospect of bringing together philosophy of science and cognitive developmental psychology in the service of science education is exciting and promising. However, to fulfill the promises, the various parties must pull in the same direction.

Gopnik is one of the most explicit of the cognitive psychologists on cognitive continuity and her conceptual change account of learning – the theory-theory - is that, “A person’s theory is a system that assigns representations to inputs...” These representations are distinctive in having “...abstract, coherent, causal, ontologically committed, counterfactual supporting entities and laws...”. Moreover, “The representations are operated on by rules that lead to new representations; for example, the theory generates predictions.” (Gopnik, 1997, 43)

The most sophisticated attempt to bring together psychology with the new *model-based* view is Giere (1988, 1999). His account is that a theory is a family of models and that a model is an abstract mathematical entity. Giere's models include those envisioned by Suppe but could include a broader range of other mathematical structures.

We do not want to worry further here whether Suppe’s models are the same kind of creature as Giere’s, nor whether Gopnik’s representations have anything to do with Suppe’s representation theorems. We simply want to alert the reader to the discrepancies that exist in terminology, and probably in underlying views. While the recognition that “models are essential to science” is a potentially valuable discovery, it risks sowing confusion since there are many different meanings attached to “model”.

We can readily distinguish at least five meanings that are prevalent in the literature in science studies and science education.

- Model as mathematical descriptions
- Model as physical analogues
- Model as iconic
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In addition, models can either be “mental”, i.e., within the cognitive system of a teacher or learner, or can be represented in a publicly accessible fashion.

We will begin to delve into this question by asking when an external mathematical model is required in place of a mental model. This may help to illustrate the first sense of model and the issues it raises. Here we draw on the work of Profitt and Gilden (1989) on the understanding and misunderstanding of rotating objects. The simplest problems in mechanics have only one relevant parameter, the location of the center of mass of the object. However, when rotating objects are considered, the distribution of mass sometimes becomes relevant. Given two objects sliding down a frictionless plane, their distribution of mass is irrelevant. In contrast, given two cylinders of the same size, shape and mass, on an inclined plane, one still needs to know the **distributions** of mass in order to predict which cylinder will roll to the bottom first. Two cylinders of may have the same diameter and mass, but different distributions of mass. One example would be a solid wooden cylinder and a hollow metal cylinder of the same diameter and mass. In the latter all of the mass is concentrated at the periphery, and the latter will roll more slowly down an inclined plane than the former.

In their studies, a variety of subjects were able to provide correct answers much more frequently to the one parameter problems than to the two-parameter problems. Most telling was that when the two-parameter problems were presented to high-school physics teachers and the teachers were forced to answer rapidly, their answers were no better than those of undergraduates without time constraints.

Summarizing:

- Given problems about rolling cylinders in which mass distribution is a relevant parameter, over 80% of University of Virginia undergraduates gave incorrect responses
- Members of the University of Virginia Bicycle club did no better
- Given the same problems and required to answer immediately without calculations, University of Virginia physics faculty did no better
- Given the same problems and required to answer immediately without calculations, high school physics teachers did no better.

To quote from Profitt and Gilden's conclusion.

"...physicists have a dual awareness of the characteristics of mechanical systems. This awareness is quite interesting to observe and it is easily elicited. . . . Prevent competent physicists from making explicit calculations about such events as rolling wheels, and they exhibit the basic confusions that are found in naive observers... However, most physicists could work the problem out in a few minutes." (391)

What is required for the experts to solve the problems is the opportunity to make explicit calculations. This suggests that the most pragmatic understanding of “having a model” is “having the ability to deploy relevant equations to describe the problem.”

Evidence both from the history of science and from research on cognitive and learning indicates that while people can fairly accurately represent relations between one independent variable and dependent variable which is a linear function of the first, that any step beyond that in mathematical complexity requires explicit mathematical concepts and notation. Galileo struggled for decades to come to grips with the first non-linear relationship in the history of science, the dependence of the distance a body falls in a given time on the square of the time of fall.

There is a large body of evidence (Chi, etc.) that even those who have been formally trained in mechanics revert to erroneous informal heuristics if pressed to solve problems under severe time constraints if those problems involve non-linear equations, e.g., $y=ax^2+bx+c$. Although we know of no historical struggles comparable to Galileo's, there is also ample literature testifying that humans have difficulty with even multivariate linear relations involving more than one independent variable, e.g., $y = ax + bz + c$.

The development first of algebra and then calculus were indispensable to the rise of modern science and no science curriculum, inquiry based or not, can ignore the role of mathematics. How, and how much, mathematics to integrate is a difficult question we must address. There is in mathematics education a great deal of work on introducing calculus concepts (math of motion, space, time) in early grade levels. The commitment is to locating the ‘Big Ideas’ in mathematics and then thinking hard about how to design a developmental sequence or corridor of instruction that leads to increasingly sophisticated understandings. The bottom line for us is that the integration of science and mathematics needs more attention!

In addition to these older historical developments, as indicated earlier the development of the computer has provided another indispensable tool for constructing mathematical models and provides another host of questions about teaching and integration of computers and science education.

The second sense of model, physical model, is equally familiar but quite different. Physical models have sometimes been indispensable in scientific discovery, e.g., the billiard ball model of gases and Watson and Crick's physical construction of possible models of DNA.

Fuller discussion of physical and other types of model are essential, but are beyond the scope of this paper. While we believe that our classification is useful, it is important to bear in mind that a model may have characteristics of several different kinds. For example, Maxwell used a picture (visual model) of an imagined (mental model) physical structure (physical model) to arrive at his equations (mathematical model). See (Nersessian, 1992 p. 62,)

Characteristics of Models

Woody (1995) identified four properties of models: approximate, projectability, compositionality, and visual representation. A model's structure is approximate. In other words, the model is an approximation of a complete theoretical representation for a phenomenon. The model omits many details based on judgements and criteria driving its construction. In many cases the model omits many variables that we know are relevant, but whose contribution is (believed to be) minor in comparison with the factors that are included in the model. (See Harte, 1988)

The second characteristic of models according to Woody is that they are productive or projectable. In other words, a model does not come with well-defined or fixed boundaries. While the domain of application of the model may be defined concretely in the same sense that we know which entities and relationships can be represented, the model does not similarly hold specification of what might be explained as a result of its application.

Woody further argues that the structure of the model explicitly includes some aspects of compositionality. There is a recursive algorithm for the proper application of the model. Thus, while the open boundaries of the model allows its potential application to new, more complex cases, its compositional structure actually provides some instruction for how a more complex case can be treated as a function of simpler cases. Finally, in Woody's (1995) framework, a model provides some means of visual representation. This characteristic facilitates the recognition of various structural components of a given theory. Many qualitative relations of a theoretical structure can be efficiently communicated in this manner.

Our taxonomy of models and their apparently disparate nature might lead readers to wonder if anything unites them other than the label. We believe that the common element to all models is that they are external aids to reasoning--they are cognitive prostheses. 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)

Adopting a purely language-based perspective for the framing of scientific theories has proven unsuccessful, and have led to the rejection of Tenet 7, the assumption that the best way of representing scientific theories is as a set of sentences in a formal logical language. Closely related is the observational-theoretical (OT) distinction. (Tenet 1) As discussed earlier, language-based perspectives maintained that the observational language of science can and should be distinguished from the theoretical language of science. Hanson (1957) was one of the first philosophers to advance the distinction between 'seeing as' and 'seeing that', the first grounded in purely sense perception observation, the second grounded in observation accompanied with background knowledge. That is, what we see is based on what we know and believe. Subsequent research on children's conceptual understandings have shown how powerful prior knowledge can be in shaping and influencing the learning of science.

Using models to communicate the theoretical structures of science stand as an alternative to the communication of scientific knowledge claims solely on the basis of language. Philosophers of science refer to the problem of language as a basis for

analyzing the theoretical structures of science as the observational/theoretical (OT) distinction problem. We now turn to a discussion of the OT problem and the implications it has for framing inquiry in science education.

Critical examinations of the structure of scientific theories also revealed that not only was it hard to make the OT distinction, it was equally difficult to come to terms with the observable and non-observable entities of theories. Van Fraassen (1980), among others, maintains that while one may elect to believe in the observable entities of a theory (e.g., age of earth, laws of motion, gas laws, anatomical structures), one may choose to remain agnostic with respect to the claims a theory makes about unobservable entities (e.g., alleles, cognitive schemata, neutrino capture). This view of the nature of science is labeled ‘semantic realism’ and it is a view that embraces the central role of mathematical languages in the representation of science (Suppe, 1998).

We would argue that a similar clarity in terms of observation language should be considered when rethinking the role of inquiry in science education. The traditional science education approach has been to get students to distinguish observation from inference – an approach rooted to Michael Faraday’s infamous exploration of the burning candle, and later adopted as the initial investigation of 1960’s NSF sponsored ChemStudy. While a distinction between observation and inference may be important for the design and interpretation of experiments, the role of observational language in statements of theory and construction of models is quite another matter.

Scientific inquiry has over the last 200 years become less and less dependent on direct sense perception acquisition of data. Increasingly, scientific inquiry relies on theory-driven methods of data collection, theories typically embodied in the tool and instruments employed by scientists. New scientific tools and technologies, like that used in GIS inquiries, have embedded visualization techniques as a corner stone for both the investigation and representation of scientific claims. Referred to as ‘inscription’ devices used by scientists, the visual representation of scientific evidence is an important language component of the sciences. Shapere (1980) in his exploration of the role theory has in technologically-rich scientific observation (e.g., neutrino capture experiments) maintains that any scientific observation naturally contains theories about the source, transmission and reception of observational information. An observation is deemed

reliable and accurate, or scientific, if and when scientists have accounted for how information transmits from source to receptor without interference or distortion of the information. Galileo encountered such challenges as his claims about mountains on the moon were attributed to distortions of light caused by the lenses of his telescope.

A challenge for obtaining a proper perspective of scientific inquiry in science education is how to contend with the transition from sense perception based science at early grade levels (e.g., K-3) to theory-driven based science at later grade levels (e.g., 4-12). We can also conceptualize the transition problem within a specific domain of inquiry or instructional unit. That is, how ought we engage students in the phenomena of the natural world? Here we are calling attention to the recognition of patterns as well as to the concrete and abstract elements of science. Beyond the question of promoting valuable motivation for learning, should inquiry units always begin with or sustain a commitment to sense perception based exploration of phenomenon? There is a strong sentiment among some science educators that engagement with phenomenon is critically important for sustaining inquiry. If so, the questions we are raising concern what are the important features of scientific phenomenon and how do we conceptualize distinctions between perceptual and non-perceptual or hidden observational phenomenon in science lessons. What patterns of nature are revealed by our senses and which are hidden from or fooled by our senses? Louis Wolpert in his book *The Unnatural Nature of Science* claims that science is fundamentally a break from common sense. What we see is shaped by what we know.

What came to be recognized and understood through historical and contemporary case studies of scientific inquiry was that the move from experimental data to scientific theory was mediated by dialogic communication. What stands between data and theory are models. Model-based views of the nature of scientific inquiry allow the inclusion of psychological processes where the received view did not. Model-based views recognize that argumentation discourse processes serve to define dialogic communication. By standing between theory and data, models can be influenced by both data revisions and changes in theory commitments.

Lab investigations situated in immersion units afford such opportunities for data revision and theory change. Thus, experiment and theory structure are important

elements of the nature of scientific inquiry but now must be understood in relation to the dialectical processes that establish data as evidence and then take the evidence to forge explanations. The implication for high school laboratories is that science education should provide more opportunities that lead to model-based inquiry and support the dialectical processes between data, measurement, and evidence on the one hand, and observation, explanation, and theory, on the other. In such immersion units, students can be enticed to experiment for reasons and reason about experiments.

Philosophy of science and the learning sciences: the cases of constructivism³

While some philosophical disputes, such as those about the nature of models and theories, are important and relevant for science education, others are not. In particular, we believe that the debates over metaphysical constructivism are irrelevant to teaching and if we can distinguish them from other cognitive constructivism, an important step forward will have been achieved. Recent developments in the design of learning environments that support learners' acquisition of scientific reasoning, argue for active engagement of learners in the process of reasoning and for embedded assessment activities that make thinking visible.

This may be a more generally useful exercise, of course, since it seems to us that there is not sufficient clarity about the variations on constructivism, let alone their relations and implications. We also believe that an understanding of the various elements and kinds of constructivism will be helpful in evaluating what is required of teachers in implementing full inquiry/immersion units or any other curriculum that incorporates the important elements of constructivism delineated below. What views teachers hold about constructivism will effect not only the content of what they teach and the methods they use, but also what they take as the goals of science teaching.

There are a wide range of terms (Fosnot 1993, Gianetto 1992, Glasson 1992, Goldin 1992, Mathews and Galle 1992, Mathews 1994 O'Loughlin 1992,1993, von Glasersfeld 1990, 1992), we are sure we will offend some authors by using the following

³ Some of the material in this section is derived from (Grandy, 1993)

distinctions rather than theirs. We distinguish cognitive constructivism, and metaphysical constructivism, both of which trace back to the work of Kuhn.

Cognitive constructivism is the view that individual cognitive agents understand the world and make their way around in it by using mental representations that they have constructed. What they could in principle construct at a given time depends on the conceptual, linguistic, and other notational resources, e.g., mathematics and graphing, at their disposal and on their current representations of the world that they have constructed through their personal history. What they actually construct depends also on their motivations and on the resources of time and energy available to devote to this particular task. This view derives from Kuhn's insights that perception is influenced by theory, and that theory evaluation always takes place in a context that includes competing theories.

By metaphysical constructivism we mean the (collection of) views that the furniture of the world is constructed by us. This view can be subdivided into the individualistic, which postulates individual constructions of individual worlds, and the social, which postulates social constructions of shared worlds. This view typically contrasts with metaphysical realism, the view that (much of) the furniture of the world exists independently of minds and thoughts. There are some obvious issues for the social sciences that we will not explore here, since social institutions are clearly human creations; the implications for geography or psychology or human biology are unclear and will also not be explored here. This view stems from, or at least is often thought to be supported by, the misinterpretation of Kuhn's work alluded to earlier. If one interprets Kuhn as thinking that "scientific decision making is basically a political and propagandistic affair, in which prestige, power, age, and polemic decisively determine the outcome of the struggle between competing theories and theorists" (Laudan, 1977 p. 4), then teaching should not emphasize distinctions between good reasons and bad, nor good arguments and bad, but rather emphasize arguments that persuade and those that do not, for whatever reasons. There is a subtle distinction between giving approximately equal weight to experiment, interpretation of data and argumentation, and giving less weight to experiment and more to interpretation and argumentation. We view it as essential that inquiry retain the importance of experimentation as providing an access to the world and not simply as a source of rhetoric.

Metaphysical realism itself comes in a range of positions on the optimism/pessimism scale with regard to the knowability of the structure. Optimistic metaphysical realism holds that not only does the universe have an intrinsic structure, that God used a blueprint if you like, but that the structure is knowable in principle by humans-- we could understand the blueprint. A less optimistic, though still guardedly hopeful, version would be that we may develop representations which are approximately correct descriptions of some aspects of the universe. How either of these positions is justified philosophically is a matter we will not linger over here, for our main point is that these issues are irrelevant for science education once we understand fully the implications of cognitive constructivism.

A metaphysical realist who accepts cognitive constructivism must recognize that whatever knowledge is attained or even attainable about the ultimate structure of the universe must be represented in the constructions of the cognizer. While accepting cognitive constructivism has very important consequences for the teacher, which we will elaborate on shortly, once you have embraced cognitive constructivism it makes very little difference what attitude one has toward the metaphysical realist issues. However independent of us the structure of the universe may be, what we can achieve by way of producing more knowledgeable students depends on the representations they can construct. This seems to us of great importance because if Constructivism is presented as a package which includes both cognitive constructivism and metaphysical anti-realism then teachers who have longstanding philosophical inclinations toward realism will find the package unpalatable. Cognitive constructivism is a relatively empirical theory which has strong evidential support from psychology, artificial intelligence and education; metaphysical realism is a venerable philosophical doctrine supported by philosophical arguments, and subject to equally venerable philosophical objections.

Accepting cognitive constructivism has very significant consequences for understanding the tasks, and the demands of the tasks, required of the science teacher. (Bloom 1992). All science teachers have, and must necessarily always have had, a philosophy of science--a set of beliefs about the nature of scientific inquiry, of scientific progress, of scientific reasoning, of scientific data, theories, and so on. Often this has been somewhat unconscious and implicit, often acquired unreflectively along with the

content knowledge in science classes. And often, in the past at least, this philosophy of science incorporated beliefs in the continuous linear progress of science, of the logical empiricist inductive scientific method, in the immutability of scientific facts, in scientific realism, perhaps even metaphysical realism, and so on. It has often included the philosophy of science education which is described as direct teaching, (Duschl 1990) or, as we think of it, the modified Dragnet theory of teaching. Unlike the old Dragnet show we don't just give them the facts, but on that model we do just give them the facts, definitions and theories, and nothing but the facts, definitions and theories.

Whatever other positions one adopts in philosophy of science, to accept *cognitive* constructivism means recognizing that each student constructs a representation based on their experience, including but by no means limited to teachers verbal input. The teacher must assess the extent to which the student's representation is isomorphic to the teacher's, but of course cognitive constructivism applies reflexively and the teachers have no direct infallible access to the students' representations but instead construct their own representations of the students' representations. Since one of the typical student's motivations, for better or worse, is to please the teacher it may also be valuable for the teacher to construct a representation of the student's representation of the teacher's representation.

The practical issues of this process need to be discussed much further, but we want to make some general pragmatic points about the process. Teachers are necessarily pursuing this process under severe time constraints and must repeatedly balance the potential value of further exploring the student's representation in all of its detailed uniqueness against categorizing the students' representation as sufficiently similar to others seen in the past to allow a particular course of further instruction to be developed without further investigation.

Of course that is only part of the task, for the teacher may well need to understand also why the student has constructed that particular representation. The divergence from the desired kind of representation may result from lack of the tools to construct an alternative, lack of accepted evidence that the current representation is insufficient or lack of motivation to construct an alternative (Ames 1990). The next step to bringing about desired change will likely depend on which of these factors is prevalent, and this

implies that the teacher must have an understanding of motivational psychology, of the evidence the student accepts, what the student counts as evidence, and on what conceptual tools the student can make use of. If this is correct, then the conceptual change movement was in the right direction, but the process of instigating conceptual change in the student is more complicated than was initially recognized. (Cf. Clement 1982)

The Learning Sciences

Conceptualizing model-based science is prompted by cognitive science research demonstrating that higher-level thinking or reasoning is domain specific and specialized (Bransford et al, 1999). Research on learning with an eye toward informing educational processes suggests that we must attend to 4 types of knowledge:

- declarative “what we know” knowledge,
- procedural “how we know” knowledge,
- schematic “why we know” knowledge, and
- strategic “thinking about thinking” knowledge.

Given this deeper understanding of learning we can better appreciate the request that an important dynamic in the science classroom, and all classrooms for that matter, is to make students’ thinking visible. The application of theory change processes to science education developed a focus on conceptual change teaching (Posner, Strike, Hewson & Gertzog, 1982). A consideration for the role dialectical processes have in science and in science learning led to the development of a focus on conceptual change teaching that was embedded both in motivating and relevant curricular contexts and in learning environments that promoted meaningful learning and reasoning (Pintrich, Marx, & Boyle, 1993).

Robert Glaser (1995), in a major review of how psychology can inform educational practice develops and outlines the components of a coherent learning theory that can inform instruction and illuminates how Kuhn’s approach might be achieved. He identifies 7 research findings that inform us about the structure and design of learning

environments – aspects of which are further elaborated in *How People Learn* (Bransford, et al, 1999).

1. *Structured Knowledge* - "Instruction should foster increasingly articulated conceptual structures that enable inference and reasoning in various domains of knowledge and skill" (Glaser 1995, 17).

2. *Use of Prior Knowledge and Cognitive Ability* - "Relevant prior knowledge and intuition of the learner is . . . an important source of cognitive ability that can support and scaffold new learning . . . the assessment and use of cognitive abilities that arise from specific knowledge can facilitate new learning in a particular domain" (p 18).

3. *Metacognition Generative Cognitive Skill* - "The use of generative self-regulatory cognitive strategies that enable individuals to reflect on, construct meaning from, and control their own activities . . . is a significant dimension of evolving cognitive skill in learning from childhood onward . . . These cognitive skills are critical to develop in instructional situations because they enhance the acquisition of knowledge by overseeing its use and by facilitating the transfer of knowledge to new situations . . . These skills provide learners with a sense of agency" (p. 18).

4. *Active and Procedural Use of Knowledge in Meaningful Contexts* - "Learning activities must emphasize the acquisition of knowledge, but this information must be connected with the conditions of its use and procedures for its applicability. . . School learning activities must be contextualized and situated so that the goals of the enterprise are apparent to the participants" (p. 19, emphasis in original).

5. *Social Participation and Social Cognition* - "The social display and social modeling of cognitive competence through group participation's is a pervasive mechanism for the internalization and acquisition of knowledge and skill in individuals. Learning environments that involve dialogue with teachers and between peers provide opportunities for learners to share, critique, think with, and add to a common knowledge base" (p. 19).

6. *Holistic Situations for Learning* - "Learners understand the goals and meanings of an activity as they attain specific competencies . . . Competence is best developed through learning that takes place in the course of supported cognitive apprenticeship abilities within larger task contexts" (pp. 19 -20).

7. *Making Thinking Overt* - "Design situations in which the thinking of the learner is made apparent and overt to the teacher and to students. In this way, student thinking can be examined, questioned, and shaped as an active object of constructive learning" (p. 20).

Prominent in the components of effective learning environments identified by Glaser is recognition of the important role prior knowledge, context, language and social processes have on cognitive development and learning. Such components are not marginal but centrally important to the process of learning. Such understandings have guided many educational researchers to recognize that reasoning is socially driven. (Brown, 1992; Cobb, 1994; Rogoff, 1990), language dependent (Wertsch, 1991; Gee, 1994), governed by context or situation (diSessa, 2000; Brown, Collins and Durgid, 1989) and involving a variety of tool-use and cognitive strategies (Edelson, Gordin, & Pea, 1999; Kuhn, 1999). Putnam and Borko (2000), examines the challenges these new ideas about knowledge and learning have for teacher education, summarize these newer conceptions of learning as cognition as social, situated and distributed. It is social in that it requires interaction with others, situated in that it is domain specific and not easily transferable and distributed in that the construction of knowledge is a communal rather than an individual activity. The various programs of research conducted and coordinated by cognitive, social, developmental and educational psychologists now present a more coherent and multi-faceted theory of learning that can inform the design of learning environments (Bransford, et al, 1999). In science education, we interpret this to mean that students must have an opportunity to engage in activities which require them to use the language and reasoning of science with their fellow students and teachers – that is to engage in the construction and evaluation of scientific arguments and models through a consideration of the dialogic relationship between evidence and explanation.

Today, understanding scientific knowledge, developing abilities to do scientific inquiry and understanding the nature of scientific inquiry requires going further than

simply learning the conceptual frameworks of science. Thus, the role of laboratories has an enhanced importance more than ever because science as a way of knowing is a cultural entity. That is, the claims of science and the methods of science impact our lives in very direct ways, defining, challenging and redefining our perspectives about nature and the world. The National Science Education Standards recognize this through the inclusion of social perspectives about science and technology as a distinct content standard. The game of science, not surprisingly, has become more nuanced as scientific inquiry becomes more focused on disciplinary specializations and increasingly takes on problems concerning the human condition like hunger, risk assessment, environmental quality, disease, energy, and information technology, among others. Our high school students and their parents do indeed have a perspective and partial understanding of scientific issues and frequently espouse alternative perspectives that challenge established scientific claims. The implication is that the role of the laboratory in high school science should be more than a mechanism for teaching what we know.

The emphasis on concept and process learning in science education has, in our opinion, contributed to an image of science education that emphasizes the confirmation role of laboratory work, as opposed to a model-based role of laboratory. In a confirmation lab, the concepts and processes are presented via lecture and/or text and then a demonstration and/or investigation is conducted to confirm how the evidence links to the conceptual understanding. In this way, science education becomes final form science (Duschl, 1990) or as Schwab warned a 'rhetoric of conclusions'. What the 4 types of knowledge indicate is that a model of science learning and the goal of laboratory experiences must go well beyond the acquisition of declarative knowledge.

A strong implication from cognitive research on learning and teaching is that conceptual understandings, practical reasoning and scientific investigation are three capabilities that are not mutually exclusive of one another. Thus, an educational program that partitions the teaching and learning of content from the teaching and learning of process, cognitive and manipulative, will be ineffective in helping students develop scientific reasoning skills and an understanding of science as a way of knowing.

Another development that affects thinking about the role of inquiry in science education is the learning science research on effective learning environments. Again, in

very broad brushstrokes, the research informs us effective learning environments are those that scaffold or support learning through the use of effective mediation or feedback strategies. Research on learning has demonstrated the importance of social, epistemic and cultural contexts for learning (Bruer, 1993; Brown & Campione 1994; Pea 1993; Goldman, et al, 2002; Sandoval & Morrison, 2003). One of the implications coming out of the research is the assessment of laboratory work in science education. Another conclusion coming out of such research is that language development for learning and reasoning is critical.

Assessing Science Lab⁴

A review of the science education assessment literature indicates that the compartmentalisation of scientific learning continues to be a dominant perspective even today as measured by the contents of standardised tests used for international and national assessments in the United States. The review of research on assessment in science by Doran, Lawrenz and Helgeson (1994) shows the prominence of the traditional separation orientation. Their review of large scale international (IAE), national (NAEP) and state and provincial government assessments is a comprehensive listing of testing programs that rely on traditional distinctions and beliefs.

Historically science education has partitioned assessment of conceptual components of science from the process, practical, inquiry and attitudinal components of science. Even new assessment procedures, such as those developed in Connecticut and California, though modifying how students report and record their responses to assessment problems, still tend to evaluate in accordance with a process/conceptual dichotomy (Baron 1990; Shavelson, Baxter & Pine, 1992). Indeed, many of the tasks are adaptations of process skill activities developed by National Science Foundation sponsored curriculum projects from the 1960s.

Many recent efforts remain strongly influenced by the tradition of laboratory practical examinations. For instance, the Doran, Lawrenz & Helgeson (1994) discussion of performance assessment focuses exclusively on laboratory and inquiry skills. For

⁴ This section is derived from Gitomer and Duschl (1998).

many science educators, laboratory practical examinations are alternative assessments. Hence, it is not surprising that the perspective of performance-based assessments used in science today (Doran & Tamir 1992; Kanis, Doran & Jacobson 1990; Shavelson, Baxter, & Pine 1992) has a great deal in common with the practical examination formats promoted years ago (Hofstein & Lunetta 1982; Lunetta & Tamir 1979; Lunetta, Hofstein & Giddings 1981; Tamir 1985). As one example, the report on alternative assessment of high school laboratory skills by Doran, Boorman, Chan and Hejaily (1993) partitions skills as they relate to planning, carrying out and analysing data from investigations as well as applying results to new contexts.

Without a doubt, there is a shift away from partitioning and toward integrating curriculum, instruction and assessment. Millar and Driver (1987), for example, argue that the processes of science cannot be restricted only to those involved in investigations. Students' prior knowledge and the context in which an inquiry is set affect the ways in which students ultimately will engage in an investigation or laboratory exercise. Hodson (1993) echoes a similar concern by reminding science educators to consider the fact that all investigative, hands-on or practical approaches in classrooms occur within an epistemological context that affects students' understandings of the tasks. This position is similar to that made about the importance guiding conceptions have in the design, implementation and evaluation of scientific inquiries (Schwab 1962). The concern is an over emphasis in the curriculum on the methods of science. Beyond the processes involved in experimenting and testing hypotheses, they argue that science curricula need also to address the processes involved in the communication and evaluation of knowledge claims, processes they believe are fundamental to the learning of science and to learning about the nature of science.

Thus, changes in social values have given rise to a new generation of assessment items and instruments (e.g., authentic tasks, performance-based task and dynamic assessments) and a set of new strategies and formats (e.g., portfolios). Champagne and Newell (1994) argue that an expanded role of assessment in science ought to include consideration of three areas of performance capabilities: (1) conceptual understanding; (2) practical reasoning; and (3) scientific investigation. They offer some assistance toward understanding the ways in which assessments need to be expanded to take into

consideration the reasoning of learners. They divide the diverse roles of performance assessments into three groups:

- 1) Academic performance assessments which include traditional laboratory practical exams and other closed-ended school problems;
- 2) Authentic tasks such as BSCS's 'Invitations to Inquiry' which involve real-world, open ended tasks that involve students in question framing, experimental design, and data analysis;
- 3) Dynamic or developmental assessments given over the course of a year or several years which measures students' potential for change over time as determined by students' responses to feedback on a task.

Together, changing social values of the purpose of assessment and of the nature of school science have profound implications for science assessment and for the role of inquiry in science education. A recent trend in assessment has been that of performance assessment wherein pupils are asked to complete or perform complex investigations. Moving to performance assessments that emphasize the integration of conceptual understanding, reasoning and investigatory skills has important consequences for what comes to count as inquiry and for the kinds of inferences that are to be made about science learning and achievement. Given the new views about science achievement from the AAAS Benchmarks and from the National Science Education Standards, the redefinition of learning in terms of performances situated in specific domains poses challenges with regard to providing evidence for claims that student ability in one domain transcends any one particular performance. This is the generalizability problem in measurement.

Furthermore, increased emphasis on the role of assessment in supporting instruction and educational reform forces greater attention to the consequences of assessment than has been usual. The validation of inferences is not only required about student achievement with respect to a defined domain and construct, but evidence is needed concerning the consequences of assessment practices for supporting instructional practices that lead to more successful learning for larger groups of students. This is, in assessment terminology, the consequential validity problem.

Language Development & Argumentation in Science Education⁵

Conceived as a sociocultural process, language development in science, in mathematics, in music, or in history involves development of the syntactical, semantic and pragmatic language structures of a domain. A critical aspect to the development of reasoning in a domain is the appropriation of language in that domain (Gee 1994; Lemke 1990). The implication of focusing on data texts (Ackerman, 1985) and model-based science is that the language of science is extended beyond the narrow historical conception of language. The language of science includes mathematical, stochastic and epistemological elements as well, among others. The challenge for research in learning science is one of understanding how to mediate language acquisition in these various ways of communicating and representing scientific claims. Here again, immersion units have been found to be successful (Bell & Linn, 2000; Schauble, Glaser, Duschl, Schulze & John, 1996; Sandoval & Reiser, 2004).

A significant insight towards changing the role of laboratory that has developed over the last 50 years, and yet only partially realized at the level of the classroom, is the important role language plays in learning, and in the design of effective learning environments. For a prominent, if not central feature, of the language of scientific enquiry is debate and argumentation around competing theories, methodologies, evidence and aims. Such language activities are central to doing and learning science. Figure 1 (on page 57) presents a schematic representation of the evidence to explanation continuum and the dialectic opportunities for epistemic conversations across science lessons. Importantly, 4-6 week long full-inquiry units provide affordances to focus on the data texts of scientific inquiries. Thus, enabling an understanding of science and opportunities for appropriating the syntactic, semantic and pragmatic components of its language. The question with regard to the role of the laboratory or inquiry in high school science is the extent to which students need to be engaged in the collection of data, the analysis of data or both.

The issue is one of emphasis and educational aims with an eye toward engaging students in practicing and using scientific discourse in a range of structured activities.

⁵ This section is derived from Duschl & Osborne (2002).

The role of the laboratory is important but a proper balance must be struck between time allocated to the collection of data and the skills of measurement and time allocated to data analysis and modeling. The role of the laboratory should NOT be to confirm conceptual frameworks presented in textbooks. At the high school level, the role of the laboratory should begin to take advantage of the skills, questions and interests students bring to the classroom. That is, if the structures that enable and support dialogical argumentation are absent from the classroom, it is hardly surprising that student learning is hindered. Or, put simply, teaching science as a process of inquiry without the opportunity to engage in argumentation, the construction of explanations and the evaluation of evidence, fails to represent a core component of the nature of science and to establish a site for developing student understanding. Herein lies the importance of immersion units situated in design, problem, and project contexts.

Teaching science as an enquiry into enquiry must address *epistemic goals* that focus on *how we know* what we know, and *why we believe* the beliefs of science to be superior or more fruitful than competing viewpoints. Osborne (2001) has argued, if science and scientists are epistemically privileged, then it is a major shortcoming of our educational programs that we offer so little to justify the accord that the scientists would wish us to render unto scientific knowledge. Hence, if the rationale for universal science education lies in its cultural pervasiveness and significance, then we must attend to explaining why science should be considered the epitome of rationality. In short, the challenge is exposing the nature of science and the values that underlie it. The role of the laboratory is vital in meeting this challenge because the authority of science lies within the process of constructing the evidence and within the reasoning linking evidence to explanation.

From such a perspective, one critically important task is establishing a context in which epistemic dialogue and epistemic activities occur (De Vries et al., 2002). Fundamentally this requires creating the conditions in which students can engage in informed argumentation; i.e., to explore critically the coordination of evidence and theory that support or refute an explanatory conclusion, model or prediction (Suppe, 1998). Situating argumentation as a critical element in the design of science laboratory learning environments not only engages learners with conceptual and epistemic goals but can also

help make scientific thinking and reasoning visible for the purposes of the practice of formative assessment by teachers. Central to a view of the value of argumentation is a conception, proposed by Ohlsson (1995), of discourse as a *medium*, which stimulates the *process* of reflection through which students may acquire conceptual understanding. As De Vries states, discourse activities are important because:

In comparison with problem solving activities, they embody a much smaller gap between performance and competence. In other words, the occurrence of explanatory and argumentative discourse (performance) about concepts effectively reveals the degree of understanding of those concepts. Epistemic activities are therefore discursive activities (e.g. text writing, verbal interaction, or presentation) that operate *primarily on knowledge and understanding*⁶, rather than on procedures. (DeVries, et al 2002 64)

Epistemic goals are not extraneous aspects of science to be marginalized to the periphery of the curriculum in single lessons (Duschl, 2000). Rather, striving for epistemic goals such as the ability to construct, evaluate and revise scientific arguments attains cognitive aims as well. Yet, as Newton, Driver and Osborne (1999) have shown, opportunities for such deliberative dialogue within science classrooms are minimal. Thus, a renewed image of the role of laboratory in science ought to embrace and then include in instruction the dialectical processes that engage learners in linking evidence to explanation, i.e., argumentation.

Argumentation has three generally recognized forms: analytical, dialectical, and rhetorical (van Eemeren et al, 1996). The application of analytical arguments (e.g., formal and informal logic) to evaluate science claims is extensive and pervasive. The capstone event of applying argumentation to the sciences is perhaps Hempel - Oppenheimer's Deductive-Nomological Explanation Model (Hempel , 1965) wherein the argumentation form is used as an account to establish the objectivity of scientific explanations. Toulmin's (1958) examination of argumentation was one of the first to challenge the 'truth'-seeking seeking role of argument and instead push us to consider the

⁶ Emphasis added

rhetorical elements of argumentation. For Toulmin, arguments are field dependent; in practice, the warrants and what counts as evidence, and the theoretical assumptions driving the interpretations of that evidence, are consensually and socially agreed by the community – an idea recognized by Schwab who saw the teaching of science as an investigation of the guiding conceptions that shape enquiry.

Likewise, case studies of scientists immersed in scientific enquiry show that the discourse of science-in-the-making involves a great number of dialectical argumentation strategies (Dunbar, 1995; Latour & Woolgar, 1979; Longino, 1994, Gross, 1996). Research in the sociology of science (Collins & Pinch, 1994, Taylor 1996) has also demonstrated the importance of rhetorical devices in arguing for or against the public acceptance of scientific discoveries. In short, the practice of science consists of a complex interaction between theory, data and evidence.

The rationality of science is founded on the ability to construct persuasive and convincing arguments that relate explanatory theories to observational data. Science requires the consideration of differing theoretical explanations for a given phenomena, deliberation about methods for conducting experiments, and the evaluation of interpretations of data. Clearly, argumentation is a genre of discourse central to doing science and thus is central to *learning* to do science. (Lemke, 1990; Kuhn, 1993; Siegel, 1995; Kelly & Crawford, 1997; Kelly, Chen & Crawford, 1998; Suppe, 1998; Newton, Driver and Osborne, 1999; Driver, Newton, & Osborne, 2000; Loh, et al, 2001).

If students are to be persuaded of the validity and rationality of the scientific world-view then the grounds for belief must be presented and explored in the context of the science classroom. In short:

‘the claim ‘to know’ science is a statement that one knows not only *what* a phenomenon is, but also *how* it relates to other events, *why* it is important and *how*⁷ this particular view of the world came to be. Knowing any of these aspects in isolation misses the point.’ (Driver, Newton and Osborne: 2000)

⁷ Emphasis in the original

Such an aim requires opportunities to consider *plural* theoretical accounts and opportunities to construct and evaluate arguments relating ideas and their evidence. For as D. Kuhn (1993: 164) argues, ‘only by considering alternatives – by seeking to identify what is not – can one begin to achieve any certainty about what is.’ To do otherwise leaves the student reliant on, or skeptical about, the authority of the teacher as the epistemic basis of belief. This leaves the dependence on evidence and argument – a central feature of science – veiled from inspection. Or, in the words of Gaston Bachelard (1940), the essential function of argument is that, ‘two people must first contradict each other if they really wish to understand each other. Truth is the child of argument, not of fond affinity.’ (page?) Indeed, Ogborn et al. (1996) show elegantly how one of the fundamental strategies of all science teachers is the creation of difference between their view and their students’ view of phenomena. For without difference, there can be no argument, and without argument, there can be no explanation. Within the context of science, dedicated as it is to achieving consensus, it is argument, then, that is a core discursive strategy, and a *sine qua non* for the introduction of argument is the establishment of differing (i.e. plural) theoretical accounts of the world. This is not to suggest that argument is something, which is unique to science. Argument plays a similar function in many other disciplines. Rather, the intent is to show that argument is as central to science as it is to other forms of knowledge and, therefore, cannot be ignored in any science education.

Mitchell (1996) is helpful in this matter by distinguishing between two types of argument - regular and critical arguments. Regular arguments, she states, are rule-applying arguments that put forward applications of theories that are not in themselves being challenged. Such arguments are generally predictive and a central feature of the work of scientists. These arguments are of the kind recognized by the logical positivists, and also appear in the Kuhnian framework of normal science. In contrast, critical arguments do challenge the theories and ideas but have as a fundamental goal the refinement of existing theories or introduction of alternative ideas and not the defeat of another. In the moral community that is science, personal conflicts and aspirations are always secondary to the advancement of knowledge.

We must remember, therefore, that initial efforts with engaging children in argumentation will require setting ground rules to avoid, for instance, *ad hominem* arguments that attack the person and not the ideas (Dillon, 1994). Such preliminary attempts to initiate argumentation practices will also require modeling and practicing the standard inductive (argument by example, argument by analogy, argument by causal correlation) and deductive (argument from causal generalization, argument from sign, syllogisms) forms of argument. Worth mentioning at this point is the research (Duschl, Ellenbogen & Erduran, 1999) that shows children do seem to have a natural tendency to engage in such inductive and deductive forms of argument when a sound context is provided.

Thus, (Cohen (1994) seeing argumentation as war is an ineffective and inappropriate metaphor for promoting dialogic discourse – a metaphor that must be explicitly countered when initiating the contexts for argument in the classroom. The alternative is to envision argumentation as a process that *further*s inquiry and not as a process that ends inquiry. Thus, alternative and more apposite metaphors for Cohen (1995) include argumentation as diplomatic negotiation, argumentation as growth or adaptation, metamorphosis, brainstorming, barn raising, mental exercises for the intellect or roundabouts on the streets of discourse. Science as a way of knowing does seek consensus on matters but, more often than not, progression in scientific thinking involves the use of critical arguments and processes that are more akin to diplomatic negotiation than to conflict. In this way, lab based science can be a dialogic process.

Harvey Siegel (1995) in “Why should educators care about argumentation?” takes the position that if one ideal of education is the development of students’ rationality, then we must be concerned not only with how students reason and present their arguments but also with what students come to consider as criteria for good reasons. Siegel sees argumentation as the way forward because of the correlation between the ideal of rationality and the normative concerns and dimensions of argumentation and argumentation theory. He writes, “Argumentation . . . is aimed at the *rational* resolution of questions, issues, and disputes. When we engage in argumentation, we do not seek simply to resolve disagreements or outstanding questions in any old way Argumentation. . . is concerned with/dependent upon the *goodness*, the *normative status*,

or *epistemic forcefulness*, of candidate reasoning for belief, judgment, and action.” (p 162, emphasis in original). Thus the second concern with the introduction of argumentation is the necessity to model effective arguments in science, to expose the criteria which are used for judgment such as parsimony, comprehensiveness and coherence, and why some arguments are considered better than another. For instance, given two arguments to explain the 24-hour rotation of the Sun and stars why do we pick the argument that it is the Earth that is moving rather than the Sun and stars?

Critically important to using argument constructively is allowing learners to have the time to understand the central concepts and underlying principles (e.g. the “facts”) important to the particular domain (Goldman, et al, 2002). In other words, a necessary condition for good arguments is a knowledge of the “facts” of a field as otherwise there is no evidence which forms the foundation of a scientific argument. Alternatively, students must be provided with a body of ‘facts’ as a resource with which to argue (Osborne, Erduran, Simon and Monk, 2001). However, argumentation does not necessarily follow from merely knowing the “facts” of a field. Equally important is an understanding of how to deploy the “facts” to propose convincing and sound arguments relating evidence and explanation. Herein lies the need for learners to develop strategic and procedural knowledge skills that underpin the construction of argument. Herein lies the need for the laboratory to be situated into immersion units in high school science programs.

In summary, the challenge is providing teachers and students with tools that help them build on nascent forms of student argumentation to develop more sophisticated forms of scientific discourse (Duschl et al, 1999; Osborne, Erduran, Simon, & Monk, 2001). Such tools need to address the construction, coordination, *and* evaluation of scientific knowledge claims. Equally important, as Siegel (1995) argues, is the need to address the development of criteria that students can employ to determine the goodness, the normative status, or epistemic forcefulness of reasons for belief, judgment, and action. What has been presented is that the central role of argumentation in doing science is supported by both psychologists (Kuhn, 1993) and philosophers of science (Siegel, 1995; Suppe, 1998) as well as science education researchers studying the discourse patterns of reasoning in science contexts (Sandoval & Reiser, 2004; Bell & Linn, 2000;

Driver, Newton & Osborne, 2000; Hogan, Nastasi & Pressley, 2000; Kelly, Chen, & Crawford, 1998; Kelly & Crawford, 1997; Lemke, 1990).

Designing learning environments to both facilitate and promote students' argumentation is, however, a complex problem, for the central project of the science teacher is to persuade students of the validity of the scientific world-view. Conceived of in this manner – as a rhetorical project – the consideration of plural enterprises may appear to undermine the teacher's task and threaten the learner's knowledge of 'the right answer'. Moreover, normal classroom discourse is predominantly monologic and it is difficult for teachers to transcend such normal modes of discourse. Therefore, changing the pattern and nature of classroom discourse requires a change both in the structure of classroom activities and the aims that underlie them. Laboratory style investigations embedded in immersion units are the way forward.

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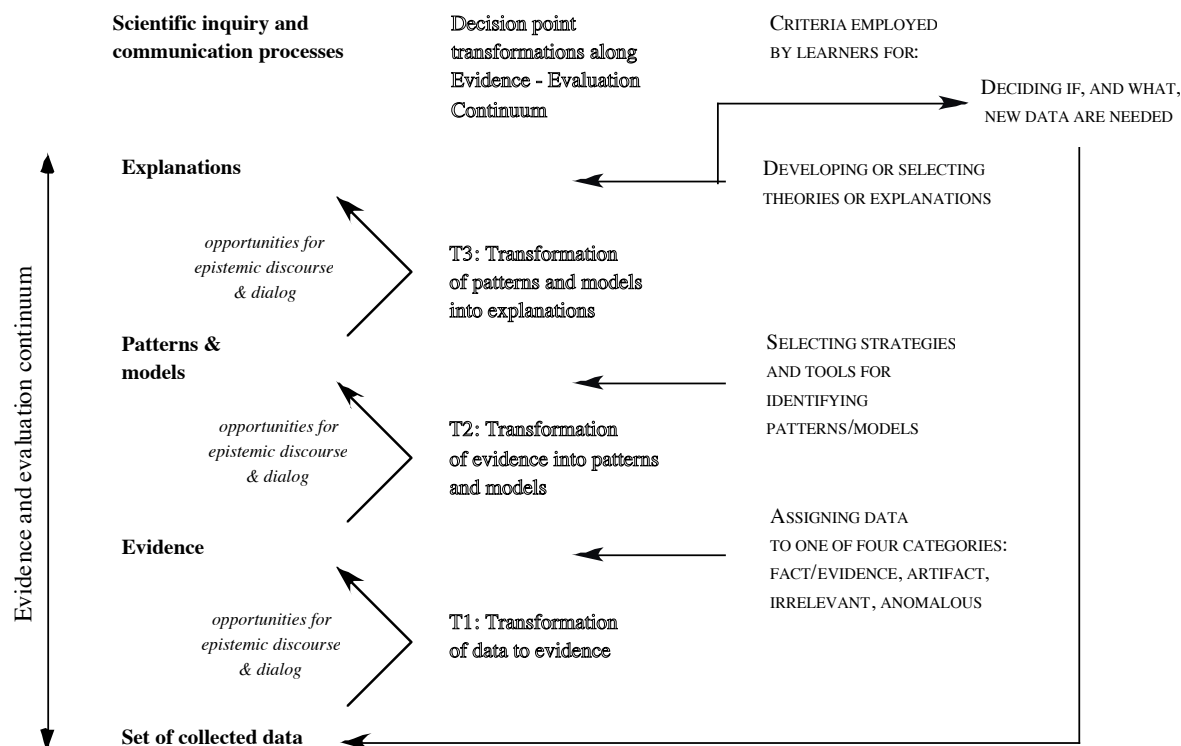


Figure 1. Schematic of Evidence-Evaluation continuum model for consideration of epistemic dialog opportunities