Inquiry Learning, Modelling and a Philosophy of Chemistry Teaching

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Abstract

Scerri and Erduran (2002) recently resurrected the question: How is knowledge developed and justified in chemistry? Scerri (2003) denies a role for constructivism in chemical education even though chemistry courses use humanly constructed models to represent sub-microscopic particles. The unobservable nature of most chemistry means that humanly constructed mental imagery is an essential element in chemical descriptions and explanations Scientific models begin life as mental models and help chemists and students develop and learn chemistry. This paper claims a role for history, philosophy and epistemology/ontology in chemical education. The paper argues that most chemical models are negotiated by experts and teachers and are interaction products of prior knowledge and experiences, current problems and evidence and reflect the preferences and commitments of their makers. Thus, constructivism deserves a place in the epistemology and philosophy of chemistry.

Paper presented at the annual meeting of the Australian Association for Research in Education—New Zealand Education Research Association held in Auckland, New Zealand, 30 Nov.—3 Dec. 2003.

Inquiry Learning, Modelling and a Philosophy of Chemistry Teaching

Inquiry Science

Inquiry is the ability to think and work scientifically and is recommended by science and education leaders in Australia (DEST, 2002), the United Kingdom (Millar & Osborne, 1998) and the United States (AAAS, 2001). Scientifically minded people value-add to science, technology and society because they are curious and ever trying to make sense of the world around them. For these reasons, earth, life and physical science are standard fare in school and university. But why is scientific thinking so important? One answer is that scientific people ask questions and investigate problems, collect and interpret data, search for explanatory patterns, and communicate new ideas. While this list of actions is not meant to be in order, complete or prescriptive; it does represent some of the things scientific people may do and one of the ways they may do them. Scientific thinking is valued because it builds on prior knowledge, relevant past experiences, and consensus ideas of what counts as knowledge. It also takes account of aesthetic preferences, personal beliefs, interests, and societal values when solving problems and interpreting new phenomena (Strike & Posner, 1985).

Science is successful because its theories are built on verifiable evidence and its practitioners insist that its predictions be testable in unambiguous ways (i.e., falsifiable; Popper, 1968). Success in science also depends on the intense scrutiny that the science academy brings to bear on new processes and theories (e.g., cold fusion; Peat, 1989). Thus,

when we start talking about successful and failed scientific revolutions (Kuhn, 1970), we are immediately confronted with questions like, 'what is scientific knowledge and how is it created and refined? Indeed, how does science change and grow?' The fact that science changes has implications for how it is taught and learned and these questions are important to philosophers of science, scientists and science educators because science is not as orderly and predictable as many people think (Chalmers, 1999). The puzzling and abstract form of many science problems is, in fact, an asset. The ill-defined character of new problems mobilises the adaptability and creativity that is science's greatest strength and the source of its many innovations. This brings us to the question that stimulated this paper: 'What do we mean when we advocate scientific inquiry in school and undergraduate chemistry courses? How does inquiry fit with the current views of how chemistry works? And, what are the philosophical dimensions of thinking and learning in science?'

Constructivist Thinking

Learning by Experience

Traditional earth, life and physical science courses permeate school and university curricula; but do they promote inquiry and scientific thinking? Currently, the most widely accepted inquiry method is constructivist thinking; however, constructivism is resisted and even condemned by some chemistry philosophers (Good, 1999; Scerri, 2003). To begin with, it must be said that constructivist science is not discovery science. Inquiry-based constructivist learning encourages students to explore and discover the objects, processes and theoretical knowledge available to them. An example is the pattern that emerges when soluble chlorides are mixed with silver nitrate: a dense white precipitate appears. After testing many chlorides, most students conclude that mixing silver nitrate with a soluble chloride always produces a precipitate. But students cannot test every chloride; nor can they easily discover whether the other halides also produce an insoluble silver salt. Inquiry is useful but it has limitations; particularly, when we try to generalise outcomes like the test for chlorides.

Chemistry (and also biology) contains so much factual information that students cannot be expected to find it all by experience. At best, inquiry can identify trends that need to be researched to establish patterns; and here, teachers and textbooks are important resources. Constructivists do not claim that students can induce or deduce the theories that took great scientists decades to construct. In practice, creative teachers design interesting and viable experiments, ask questions, provide thinking hints and supply essential information on a "need to know" basis (Appleton, 1993). Some teachers are prone to tell students all about their own interests; but the criterion for providing information is the students' desire or need to have it. Expert teachers know how and when to do this.

Constructivist teachers encourage the use of open investigations that are safe, practical and educationally beneficial. They ask their students to think, wonder why, make testable predictions, and carry out thought-experiments. When their students interject with, "what if we tried …", they assess the practicality of such an investigation and, if it is safe and economic, let the students design, conduct and interpret the experiment. Whether the experiment will or will not work is not the criterion to proceed: we all learn something from our mistakes and a poorly designed experiment may point the way to a better one. Scientists follow their hunches and imagination and few of their hunches succeed; but the ones that yield new knowledge are celebrated.

Most important of all, constructivist teachers teach students *in* science, not *about* science. Learning in science is an immersion processes – it includes thinking, reading, arguing and investigating. Still, constructivism recognises that certain experiences, facts and processes are unavailable to students for reasons of safety, time and economics. In these cases creative teachers scaffold students as they search, find and access the information that builds conceptual knowledge. What constructivist teachers decry is telling students what they could find for themselves; they reject didactic descriptions that lack explanations, shun recipe-book laboratory work that verifies textbook knowledge, and avoid activities where the student rote-learns algorithms (sometimes known as 'plug-and-chug' problem solving). And constructivist teachers insist on assessment that encourages meaningful learning. Student minds will be focused on learning if the assessment concentrates on problems that require theory, content and thinking. This usually means that constructivists eschew multiple choice (or multiple guess) questions.

Another point of departure between traditional chemists and constructivist educators is the prominence afforded to content and practical work. Some school and university chemistry courses are so content laden that content and instrumental skills seem to be the desired outcomes. Scientific thinking grows out of understanding how we construct, sustain and revise knowledge and change alternative conceptions. Information is important but facts are the bricks, timbers and tiles, not the walls, roof or the house itself. Extensive chemistry education research has demonstrated 1) the benefits of open-ended learning (e.g., Finster, 1989, Harrison & Treagust, 2000a), 2) the prevalence of alternative conceptions that inhibit learning (e.g., Coll & Treagust, 2003; Garnett, Garnett & Hackling, 1995; Gabel, 1999), and 3) conceptual change strategies that encourage meaningful learning (Harrison & Treagust, 2001; Novak, 1984). It is one thing to know what is lacking in chemistry teaching (over 40 studies in the last 20 years), but it is quite another to plan and implement effective constructivist content and pedagogy. Students are entitled to know how we derive and justify key items of chemical knowledge and they also are entitled to know why we treat current knowledge as intelligible, credible and a source of fruitful predictions.

Constructivist Criticisms

The critical press that constructivism currently receives from some chemical educators (e.g., Scerri 2003) is due, in part, to the critics' shortfall in understanding of constructivism. It is imperative that critics understand what they are criticising and it is not sufficient to cite philosophical wars, slogans, or demolish straw men (e.g., Scerri's analogy of "weight reduction … 'before and after' snapshots"). If one wants to critique the differences between traditional and constructivist teaching, then Yager (1991) and Yore (2001) provide broader and richer comparisons than Scerri chose. But the division between chemists and educators on inquiry learning and constructivism is more fundamental than lists of comparative descriptors. It cuts to the heart of how we see, construct and justify knowledge – both in a scientific and an educational context. And this process has a distinctly philosophical flavour.

Constructivism is an epistemology. *The Oxford Reference Dictionary* defines it as a *philosophical* concept dealing with "the theory of knowledge, esp. with regard to its methods and validation" (Pearson & Trumble,1996, p.473). von Glasersfeld (1992) links epistemology with "UNDERSTANDING of the RATIONAL kind" (p.29 emphasis in original) while Denzin and Lincoln (1994) describe epistemology as the standard of "how we conceptualise our reality and our images of the world" (p.6). Still others explain epistemology as 'knowing about

knowledge' and understanding what we know and how we know it. But these definitions have two-edges: epistemology is our philosophical concept of how we know what we know *and* it is what we think we know about the world outside the mind. Our conceptions of the external world – interaction products of sensory input, prior knowledge and thinking – is ontology. It is therefore hard to separate epistemology and ontology and one-way of delineating the two is to call epistemology 'the looking in on what we know' and ontology is 'what we see when we look out at the world'. Thus, ontology could be called the way we visualise and model the things in the world that interest us. This looking in and looking out highlights the philosophical flavour of epistemology and ontology.

Thinking with Models

Chemistry's content, teaching and learning rest heavily on epistemology and ontology because it needs to model abstract sub-microscopic objects and processes. Chemistry can simultaneously explain chemical change at the macroscopic, sub-microscopic and symbolic levels (Johnstone, 1991) and the latter two levels always use abstract, theory-driven representations that we call models. The models can be as different as colliding elastic balls (kinetic theory); chemical equations; ball-and-stick, space-filling and Lewis models (for molecules and lattices); Brønsted-Lowry acids and bases; molecular orbital models and the Schrödinger atom. Sometimes these concepts are represented in textbooks by a series of historical or alternative models: e.g., four models of acids and bases (Carr, 1984) or five side-by-side representations of water molecules (Parry et al., 1970). Recent undergraduate textbooks relegate historical models to the museum and may treat atoms and bonding only from the Schrödinger and valence bond or molecular orbital perspectives but this ignores the fact that students have learned the antecedent models in school. As conceptual change theories explain, prior knowledge is not forgotten even when strong conceptual change has occurred (Posner et al., 1982; Tyson et al., 1997) and students do revert to previous conceptions, especially when 'replaced' models seem to solve some problems more easily. Coll (1999) reports that even chemistry lecturers revert to the octet rule when solving simple bonding problems. As Hewson (1996) argues, the status that a person ascribes to his or her available models determines which model will prevail.

The notion that chemistry models (e.g. atoms, molecules and bonds) are some form of reality exposes the flaw of scientific realism. Models do represent chemical atoms, molecules and interactions and they are extremely powerful tools for doing and learning chemistry. They allow chemists to describe, explain, and theorise the structure of matter and predict ways in which it might behave in the future. And chemistry models and their embedded theories are eminently testable. They are changeable and do change. Indeed, the essence of scientific thinking is the ability to change old models and construct new ones in the light of new evidence (Gilbert & Boulter, 2000). But chemistry research shows that this view is not held by many chemists – they view models as 'right' and fixed (e.g., Justi & Gilbert, 2002). To say that chemical models do not involve mental models of the sub-microscopic world is a fiction. To claim that chemistry's models are an absolute, correct and right representation of nature confuses our inward and outward views of the world and its parts. And it encourages didactic teaching that denies students the opportunity to customise models to suit their needs. Models are flexible thinking tools, not fixed entities. The model serves the thinker, not the thinker the model.

Mature constructivists therefore claim that models are designed and changed to encourage thinking. Imaginative chemists use models this way; however, Harrison (2001) found that more chemistry teachers than biology or physics teachers said that models should not be changed. With respect, I suggest that chemists have fossilised their models to the extent that students feel that they have to learn and preserve chemistry models and are not allowed to modify these models to suit their learning needs. This flies in the face of the modern learning theories propounded by Ausubel, Piaget and Vygotsky. The view that knowledge of the sub-microscopic world is true and real disagrees with the widely accepted conceptual change theories of Hewson (1996), Posner et al. (1982), Strike and Posner (1992), Thagard (1992) and Vosniadou (1994). These theories are summarised and critiqued by Tyson et al. (1997).

Students and chemists continually accrete, conceptually add and conceptually exchange knowledge *in their minds* and build *internal conceptual frameworks* that reflect their preference for rational and aesthetic knowledge. To claim otherwise denies the existence of personal choice, favourites, love and art. Chemists and students depend on this intricate web of model-based language for their research and learning. Students spend most of their time trying to construct credible images of atoms and molecules and interactions (and so do chemists when they write interactive software that shows ice melting and salt crystals dissolving in water). Some of the images that chemists use are balls (but atoms are not solid coloured balls!) and joining sticks (but electrostatic bonds are not rigid structures!) and the motion is slowed (but it is very fast!). The constructivist has no argument with customised models; s/he simply argues for the legitimacy of changing one's mind and one's image of reality as more or better information becomes available. Model adaptation is like a plant or animal's adaptation to its environment: creative thinking and survival depend on it. Students modify and adapt their mental models as they proceed from atoms as solid balls in Year 8 science to university chemistry where atomic orbitals are spatial probabilities that are operationalised in models like the aufbau principle. The constructivist agrees with concrete and theoretical models and lauds model-making that has context-specific pedagogical purposes. What s/he rejects is the fixed reality of models in time and space.

Summary

It suffices to say that in chemistry, philosophy↔epistemology↔(model)ontology can be represented as a continuum. At one end, thinking is philosophical; at the other end models represent reality in ways that describe and explain the atomic world. In between lies epistemological questions about the credibility, dependability and transferability of the representations we use to practice and teach chemistry. In one direction the questions are philosophical, in the other they are pedagogical; but the two are interdependent. I will now review some of the other questions raised by the philosophy of chemistry, ask whether this list is complete and then argue that constructivist epistemology is the pedagogical glue that enhances thinking, teaching and learning in chemistry.

Questions from Chemical Philosophy

A recent examination of three philosophical themes led Erduran and Scerri (2002) to insist that chemistry is a distinctive science that is not reducible to physics. There are similarities between chemistry and physics; however, the thematic differences relating to reductionism, scientific explanations and laws and the principle of supervenience support chemistry's claim that it is philosophically independent. This paper takes the three themes and uses them to

expand the debate about philosophy and epistemology in chemistry education. The first theme discusses reductionism.

Is Chemistry Reducible to Physics?

Reductionism asks, is chemistry reducible to the laws of physics or are there chemistry concepts that defy reduction to elegant equations and concise laws? In his book *QED*, Richard Feynman asserted that: "Quantum mechanics … supplied the theory behind chemistry. So, fundamental theoretical chemistry is really physics" (1985, p.5). He also says that "if you're interested in the ultimate character of the physical world … at the present time our only way to understand that is through a mathematical type of reasoning" (1999, p. 13). To counter this claim, Erduran and Scerri cite two ways of distinguishing chemistry from physics: first, they insist that while atoms have fixed properties, compound properties are neither the sum nor average of the constituent atoms; the interaction is more important than the parts. Further, compound compositions can lawfully change over time in chemical reactions and this property cannot be reduced to physics without losing critical conceptual detail. Second, they point out that conceptual models of molecules and bonds are not reducible to theoretical physics because chemical "composition, bonding and structure" involve a web of relationships and "the concept of chemical bonding seems to be lost in the process of reduction" (both p.14). Chemical knowledge and models like valence bond theory and molecular orbitals contain qualitative explanations that cannot be reduced to physics and mathematics.

If chemistry is not physics, then it should be taught in a way that celebrates its uniqueness by encouraging students to discuss and manipulate their own model-conceptions of the sub-microscopic world. And by encouraging students to remember that every model is just the best human construction at that time or for that context. No model is really true!

Are Chemical Explanations Unique?

The second issue raised by Erduran and Scerri (2002) is the philosophical uniqueness of chemical explanations. This means that there are differences, for example, between the way chemists explain electron orbitals and the ontological status demanded by quantum mechanics (Scerri, 1991). This highlights the need for a quantitative—qualitative mix in chemical explanations. Chemistry places great importance on pedagogical models (e.g., molecular and ionic lattices) and theoretical models like acids, bases and buffers. Also, Erduran and Scerri insist that the mathematical laws of physics are not isomorphous with the classificatory patterns that characterise chemistry (e.g., the periodic law with its periods, groups, blocks and trends). A case in point is the way chemistry explains the anomalous electron configurations of chromium and molybdenum in the fourth and fifth periods. This anomaly contributed to chemistry's understanding of the order of filling *s* and *d* orbitals. The periodic table is a powerful concept because even when incomplete it predicted the existence of scandium, germanium and gallium. While crucial to research and teaching, periodicity cannot be reduced to a quantifiable relationship that satisfies physics. The periodic table is a holistic model that gives chemistry coherent meaning and the period trends spawned a whole book full of analogical explanations (Atkins, 1995).

The periodic table can be presented in different formats and each form excels in specific ways: indeed, there is no "right" table (Scerri, 1991). The competition between alternative

formats is a cause of philosophical thought because it is a classic example of multiple models enhancing scientific thinking in experts and students.

Supervenience and Inductive Projection

Lastly, Erduran and Scerri insist that in chemistry, "macroscopic identity does not imply microscopic identity" (the principle of supervenience). Put simply, a macroscopic piece of matter and its isolated particles do not have identical properties (e.g., copper atoms are not red and they do not conduct electricity; Ben-Zvi, Eylon & Silberstein, 1985). Why is this so important? At an epistemological level, the family of alternative particle conceptions reported in the chemistry education literature (e.g., Garnett, Garnett & Hackling, 1995; Lee et al., 1993) is evidence of students' systematic propensity to inductively project the properties of pure macroscopic substances onto their constituent particles (Harrison & Treagust, 2002) This conception persists because students intuitively think this way and some modern textbooks even assert that isolated atoms of copper have all the properties of, say, a copper coin.

This is an example of analogical modelling breaking down because the classical and quantum worlds are so different. It seems logical to many students and some teachers to map the macroscopic properties onto sub-microscopic particles in the same way that in 1872 Medeleev analogised the properties of germanium from silicon. Analogies work when the source and target domains obey the same rules and principles, but the quantum world is not a mirror of the macroscopic world. In fact, they are philosophically different worlds and paradigms (Kuhn, 1970).

Are Models and Analogies Legitimate Scientific Thinking?

Two of Erduran and Scerri's philosophical differences between chemistry and physics concerned the representation of orbitals and bonds as realistic entities and the uniqueness of the periodic law. Orbitals, bonds, molecules and the periodic table are all scientific models. Almost every chemical phenomenon uses scale, pedagogical, iconic or theoretical models to represent the invisible interactions that take place between atoms, molecules and ions. (Harrison & Treagust, 2000b). Multiple models also are needed to explain acids and bases, redox, reactions rates and chemical equilibrium and this raises two important questions. The first question relates to epistemological efficacy; i.e., does a chosen model promote student learning and minimise alternative conceptions? And the second asks, Is the model suitably simplified or exaggerated for its recipients? Questions about models are philosophical because discussions about models often lead to debates about the legitimacy of simplification, exaggeration and analogical mapping. For instance, is an analogy limited to communication or can it heuristically lead to new knowledge? Bronowski (1973), Farber (1950) and Lorenz (1974) all answer yes, analogical models can yield new knowledge; but what type of knowledge is generated by analogy?

Analogical knowledge is not typical empirical knowledge and this raises several problems. When we use analogies, the source—target similarities are called mappings (Duit, 1991) and are classified as shared attributes (positive analogy) or unshared attributes (negative analogy). Mary Hesse (1963) proposed a third mapping called the neutral analogy. Neutral analogy can be a source of possible new relationships that raise questions and stimulate new research. But how do scientists judge the intelligibility, credibility and fruitfulness of the neutral analogy? Scientists who understand the positive and negative attributes of analogies

will probably use this knowledge to evaluate the neutral analogy. But how was the now accepted positive analogy agreed on in the first place? And, if the new relationship suggested by the neutral analogy is useful (like Kekulé's snake biting its tail), is it new knowledge or is it just a better way of organising data and ideas already held in memory? And when does the scientific community accept discovery generated by analogy? Furthermore, when the theoretical edifice suggested by analogy is established by theory and experiment, is the analogy retained by chemists or only by educators? These questions suggest that there may be significant differences between the way researchers and teachers judge analogical knowledge.

The history of science also shows that a long time may intervene between the genesis of an analogical idea and the acceptance of the resulting theory. Bronowski claims that Kepler's ideas of planetary motion were suggested by the working of a clock, but many years separated the wheels revolving in wheels analogy and the acceptance of Kepler's laws.

So, who decides when an analogy becomes credible and fruitful and what operational criteria are used to make these decisions? In chemistry, new knowledge is unique and deserves to be called a discovery; however, in chemistry education knowledge that is new from the student's viewpoint can almost be axiomatic for the teacher. Analogical models can be easily agreed on by teacher and student (see the FAR guide, Treagust et al., 1998) but are subject to intense scrutiny when debated between scientists. The philosophical distinction between research knowledge and education knowledge is important because many academic chemists also are university teachers. In other words, which epistemological or philosophical hat does a chemist wear when teaching chemistry and when researching chemistry? This has implications for education because chemists need to change their thinking hats as they move between teaching and research. Finally I ask: Are the models used to explain sub-microscopic particles equally viable in research and teaching? These questions are not yet answered by sociological or educational research and are important as we try to frame a philosophy of chemistry education.

The needed research will be philosophical because the questions probe the very nature of knowledge and thinking. It will recognise the role of constructivist thinking in science because many of the ideas referred to arose from analogy and mind-experiments. Reflecting on inquiry and constructivism, I believe that a viable case has been made for claiming that most of the knowledge of the sub-microscopic world is a product of model-based thinking about data derived from macroscopic interactions between vast numbers of atoms and molecules (Dalton, 1808-10).

History and Philosophy and Learning in Science

Those familiar with Popper (1968), Kuhn (1970) and Lakatos (1970) will know that each of these writers discusses the problems of scientific progress in historical contexts. But just adding the history of a chemical discovery to a chemistry course will not explain the growth of a concept (see Goldwhite, 1975 and Kauffmann, 1989). Explanation and discussion are needed. For example, the history of the atomic theory shows that atoms were successively modelled as solid balls (Dalton), a plum pudding (Thomson), mostly space (Rutherford), a solar system (Bohr) and quantum probabilities (Schrödinger). To explain progress like this, Popper insisted that every scientific hypothesis must be falsifiable. The historical succession of increasingly sophisticated models of atoms, molecules and bonding can be seen as a

product of falsification, theory replacement and new or re-evaluated data. Popper's falsification, however, precipitated a crisis that asked why should any scientific idea succeed? By his own tautological definition, every hypothesis is falsifiable if it is scientific; and if it isn't falsifiable, we need not even worry about it! This is an aspect of thinking scientifically where students often are left out of the philosophical loop. By their "rhetoric of conclusions" (Schwab, 1966), most textbooks assert that better models were the result of new or fuller data, an argument that Chalmers (1999) swiftly demolishes.

As chemistry education proceeds through school and university, yesterday's atomic models become today's alternative conceptions that require conceptual change teaching. Textbooks often just tell students when and who proposed a better model rather than how and why it happened. Students don't forget superseded models (Tyson et al., 1998) and neither do chemistry educators; for example, kinetic theory models retain the image of atoms and molecules as solid elastic structures at almost every level including university. This is a significant problem for students who are Dualist (Finster, 1989). Dualists look for cues that tell them which model is right instead of trying to understand which model in a set of multiple models is most appropriate in that context (Harrison & Treagust, 2000b).

Yet another problem arises when the history of a concept is simply retold: Kuhn (1970) argues that scientific revolutions tend to rewrite history and treat the previous paradigm and its problems as if they no longer existed. Science history is like world history: he who wins the war gets to write its history; and even when one has heard both sides of a story, it is evident that there is more to the story than both sides!

A successful scientific revolution reformulates the concept's theory, methods, problems and allowed solutions in ways that generate new world-views. A purely historical narrative cannot easily describe, much less explain, the change because the old and the new concepts work "in a different world" (Kuhn, 1970, p.121), speak different languages and talk "through each other" (p.132). In other words, the history of chemistry needs a philosophy to explain why and how scientists changed their conceptual and explanatory models. The image students develop of science and its processes is enriched when they share customised accounts of chemical revolutions like Dalton's atomic theory and Bohr's quantised explanation of hydrogen's spectra.

Epilogue

In this paper, many chemistry thinking and teaching questions have been asked and a few answers suggested. Chemistry teachers often feel that a philosophy of chemistry teaching is not necessary when conceptual content is the teaching focus (Erduran, 2001; Scerri, 1997). Philosophy and history appear to be the poor relations to conceptual content when chemistry is taught in schools and universities because they lack the 'whiz-bang' achievements of theoretical and practical chemistry. I recall my last year in university before embarking on my teaching journey. A respected professor told my class "take your time over the next few years but build your very own philosophy of teaching". I believe that, for me, this is still happening 35 years later.

Chemistry is a coherent science and its success in the 20th Century entitles it to an independent place in the science academy. Chemistry, however, seems to run the risk of becoming ossified in its own explanatory models and notable achievements. The explanatory coherence of the Schrödinger atom, molecular orbital theory, and its many other successful

models, exposes chemistry to an internal complacency that chemistry is somehow 'right', 'correct', 'true' and that the entities described by its theories 'really exist' as depicted. Reading chemistry textbooks and sitting in school and undergraduate classes immerses students in an aura of certainty. Constructivism agrees that there is a real world; but it takes issue with the certainty that some scientists claim for their picture of the world. Their individual mental models and the shared consensus models are simply the best models available. Without their mental models they would never have become successful chemists. But every mental model is an interaction product of piror knowledge and experiences, current problems being worked on, and the thinking processes and preferences that the scientist brings to her or his work. No research chemist would claim that all of chemistry's problems are solved or that celebrated models will not change. If a philosophy of chemistry is to grow and mature, it should keep at least one eye on its assumptions and the human element in its processes and theories. Scientists explore, interpret, argue and produce new models or change old ones.

Constructivism only asks that this process, in a less sophisticated form and detail, be shared with chemistry students. Remember, some of these students are much smarter than we are and a few will be the laureates of the future.

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