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ABSTRACT

This paper reports on an interdisciplinary theoretical framework for the characterization of models and modeling that can be useful in application to chemistry education. The underlying argument marks a departure from an emphasis on concepts that are the outcomes of chemical inquiry about how knowledge growth occurs through modeling in chemistry. An outline is presented that provides reasons why modeling is a significant goal for chemistry education, the role of models and modeling are closely examined, and some cognitive and epistemological accounts of models and modeling are exemplified. A review of the role of models in chemistry, some trends in the use of models in chemistry education, and some implications for how chemistry learning environments can be designed so that modeling can be promoted and sustained in the classroom are also included. Contains 142 references. (DDR)

Modeling in Chemistry as Cultural Practice: A Theoretical Framework with Implications for Chemistry Education

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Introduction

Traditional views of scientific inquiry focus on the individual scientist as the inquirer (e.g. Hempel & Oppenheimer, 1948). In contrast, sociocultural theories describe scientific inquiry in terms of community practices which provide the structure, communication and motivation required to sustain this inquiry (e.g. Latour & Woolgar, 1979). Knowledge construction is not an individual activity; rather, scientific communities enable the production of scientific knowledge. In the latter framework, the practice of science is considered to involve the generation, evaluation and revision of tools that facilitate growth of knowledge about the natural world.

A significant tool in the growth of chemical knowledge is modeling. Chemists generate, evaluate and revise models in explaining properties of matter and changes in matter (Hoffmann & Laszlo, 1991). In general, a model is defined as a representation between a source and a target (Boulter & Gilbert, 1996; Duit & Glynn, 1996), the target being an unknown object or phenomenon to be explained, and the source being a familiar object or phenomenon that help scientists understand the target. Models play a central role in expert scientists' reasoning and problem-solving (Clement, 1989; Larkin, 1981; Reif, 1983; Chi, Feltovich, & Glaser, 1981), and they are instrumental in summarizing data, making predictions, justifying outcomes and facilitating communication in science.

Philosophers of science, cognitive psychologists and educators alike have drawn attention to the significance of models. Models are central to many philosophers' discussions. Philosophers raise questions about the relation of models to explanations (Woody, 1995) and theories (Giere, 1991), and explore the role of models in the work of scientists, such as the case of Galileo's balance model (Machamer & Woody, 1992). Cognitive psychologists, on the other hand, study the role of models in the intellectual development of young children (Schauble, Klopfer, & Raghavan, 1991) as well as in conceptual differentiation (Smith, Snir, & Grosslight, 1992; Wiser, 1987) and perception (Bruner, 1966). They recognize that acquisition and employment of models are closely associated with the learning and use of language and analogies (Gentner & Stevens, 1983).

Although tensions have been identified in the applications of interdisciplinary approaches in education (Duschl, Hamilton, & Grandy 1990), authors (e.g. Osborne, 1996; Duschl & Gitomer, 1991; Nussbaum, 1989) agree that such applications can be informative in educational research . When we, as educators, ask the question of what scientists do and how we can translate aspects of what scientists do in the learning environment, we are essentially begging views from disciplines which target issues not only about the nature of scientific inquiry (i.e. issues in philosophy of science) but also about the nature of students' cognition in science (i.e. issues in cognitive pscyhology).

The main objective of this paper is to report an interdisciplinary theoretical framework for the characterization of models and modeling that can be useful in application to chemistry education. This underlying argument marks a departure from an emphasis on concepts that are the outcomes of chemical inquiry to how knowledge growth occurs through modeling in chemistry. In particular, the relation between cognitive and epistemological accounts of knowledge growth can inform how effective chemistry learning environments can be structured. Substantial evidence (e.g. Carey, 1985; Gopnik & Meltzoff, 1997; McCloskey & Kargon, 1988; Schwitzgebel, 1996) suggests that children's cognitive development and theory change in science might involve similar mechanisms. First, I present an outline of why modeling is a significant goal for chemistry education. Second, I examine more closely the role of models and modeling in chemisty. Third, I exemplify some cognitive and epistemological accounts of models and modeling. I review the role of models in chemistry and some trends in the use of models in chemistry education. Finally, I provide some implications for how chemistry learning environments can be designed such that modeling can be promoted and sustained in the classroom.

Engaging Students in Chemical Inquiry through Modeling

In The Same and Not the Same, the Nobel Prize winning chemist, Roald Hoffmann (1995) argues for restructuring schooling such that all students acquire an understanding of 'what it is that chemists do' (p. 228). As a chemist who has reflected extensively on the educational, philosophical, cognitive, historical and social dimensions of chemistry, Hoffmann is an exceptional scientist who recognizes the significance of fostering students' meaningful learning. Through a vast set of analyses (e.g. Hoffmann, 1993; Hoffmann & Lazslo, 1991; Hoffmann & Torrence, 1993) Hoffmann has built a case for chemistry as a distinct field of scientific inquiry. "What chemists do" is essentially the modeling of structure and function of matter in order to explain properties of matter and changes in matter. Modeling enables chemists to develop, evaluate and revise chemical knowledge. It becomes critical, then, to provide learners of chemistry with opportunities to develop an understanding of how modeling is involved in the growth of chemical knowledge.

Schwab (1958), like Hoffmann, had argued that science teaching should nurture themes, such as modeling, that characterize a science as a distinct way of knowing. The common thread between these scholars stems from a vital concern that science teaching is not doing enough to implement scientific inquiry in the classroom. This concern has been voiced in past evaluations of science education (Welch, 1979), and continues to echo throughout contemporary reform initiatives (e.g. American Association for the Advancement of Science [AAAS], 1989; National Research Council [NRC], 1996). The National Science Education Standards (NRC, 1996) specify that scientific inquiry should be a critical component of science education at "all grade levels and in every domain of science" (p. 214). Scientific inquiry is defined as "a set of interrelated processes by which scientists and students pose questions about the natural world and investigate phenomena; in doing so, students acquire knowledge and develop a rich understanding of concepts, principles, models, and theories" (p. 214). Although it is encouraging to witness at the national level the recognition of the importance of inquiry in science and science learning, effective implementation of policy recommendations in everyday classrooms is far from being complete.

Science in traditional schooling has taken the form of 'facts about the natural world', and science teaching has ensured the delivery of science as 'facts to be memorized'. When we, as educators, turn to historical (e.g. Kuhn, 1962/1970), philosophical (e.g. Laudan, 1981), sociological (e.g. Latour & Woolgar, 1986) and cognitive (e.g. Giere, 1991) analyses of science, we are faced with the overwhelming evidence that science is not a collection of facts about the natural world, and scientific knowledge is not final or immune to revision. Schwab, as a contributor to the debates in the 1960s on the revisionary nature of science, was influential in informing science education about the then emerging new perspectives on science (e.g. Kuhn, 1961/1970). Within the last 40 years since Schwab, however, research in history and philosophy of science (HPS) has elaborated further on what 'doing science' entails.

We have learned that scientific inquiry is characterized by development, evaluation and revision of theories, models and explanations through use of criteria, strategies and heuristics (e.g. Cartwright, 1983; Rheinberger, 1997). Why have we *not,* then, facilitated students' understanding of scientific inquiry as marked by development, evaluation and revision of models, explanations and theories about the natural world? Why have we *not* designed learning environments that promote the generation and use of the criteria, strategies and heuristics that drive development of models, explanations and theories? If the evidence is that scientific reasoning is domain-specific (Thagard, 1992; Nercessian, 1992), then why have we *not* encouraged students to do science in the way that scientists of a particular domain do it?

A potential reason for why we have not succeeded in achieving 'science as inquiry' is that we have not paid enough attention to how we can support growth of scientific knowledge in the classroom. Science teaching has reinforced a 'rhetoric of conclusions' (Schwab, 1964), a tradition that perpetuates the learning of conceptual outcomes -

declarative knowledge - at the expense of strategies, heuristics and processes that provoke and validate these outcomes - procedural knowledge. Although both domains are necessary in scientific reasoning (Clement 1982; Glaser, 1994; Larkin et al., 1988), science teaching has placed a strong emphasis on fostering students' acquisition of declarative knowledge. Furthermore science teaching has not devoted enough attention to the distinctions that discern knowledge generated in different fields of scientific inquiry. For instance, whereas the tendency in physics is mathematization, chemistry relies on classifications based on chemical models which explain more of the qualitative aspects of matter such as color, taste and smell (Scerri, 1996).

Students will learn 'what it is that chemists do' when they are engaged in modes of thinking and acting that characterize chemistry as a distinct domain of science. In order to implement such themes as modeling, however, we need to forge an interplay of the procedural and declarative knowledge domains of chemistry. In other words, students will be taught that matter consists of atoms, for instance, but *how* this knowledge is constructed and *why* this knowledge (and not others) counts as scientific, are critical and need to be integral parts of teaching. When students are embedded in contexts where they can develop, evaluate and revise chemical knowledge, they will act and think in ways that chemists act and think.

In engaging students in scientific inquiry, it is not enough to orchestrate the use of declarative and procedural knowledge domains of science. It is vital also to acknowledge students' background knowledge. The knowledge that students bring to the classroom play an important role in their subsequent learning. Substantial evidence on students' conceptions (Pfundt & Duit, 1994) and problem-solving (Gable & Bunce, 1994) suggest that students' ideas about natural phenomena can become obstacles in their learning. Students come into science classrooms with *their* conceptions and means of problem-solving which are often in conflict with scientific knowledge that they are expected to learn in the classroom. These conceptions are often resistant to change and persist even after years of instruction. Capturing and diagnosing students' conceptions, then, become important components of teaching 'science as inquiry'.

Let us envision what learning environments would look like if they were to sustain scientific inquiry. In a classroom where learning about the particulate nature of matter is a goal, students have opportunities to observe patterns of how matter behaves in nature. Students can and will express their conceptions. The teacher will thereby be informed about students' background knowledge and can give students appropriate feedback in revising their ideas. Students may propose explanations such as "acids are sour because they contain sharp-edged, little objects which bite the tongue." This description models an acid based on the shape of its ingredients.

In the social setting of the classroom, alternative models will emerge. For instance, another student might propose that "acids are sour because they contain slices of lemon in them." This model is based on superimposing, at the microscopic level, a concrete experience of a particular acidic substance, lemon. These models can be expressed in written, pictorial or verbal formats. However expressed, these models will be shared in a public forum and discussed with respect to their plausibility and explanatory power. The models will be contrasted and evaluated against emerging scientific criteria. For instance, students might argue about the generalizability of the models to account for a diverse range of properties observed. Does this model of an acid help in explaining and predicting its other properties, such as its reaction with metals? If it does not, how can it be revised? What strategies are needed to formulate a new model? What should the new model account for that the old one does not? Are there any features of the old model that can be carried onto the new model?

In this hypothetical classroom, students learn about the particulate nature of matter *not* because the teacher or the textbook mandate this concept as a fact, but because students gain an appreciation of this concept via modeling the structure and function of matter *themselves*. The existence of formulation, evaluation and revision of knowledge claims throughout the lessons signals this classroom as one where scientific inquiry takes place.

I have argued so far that achieving 'chemistry as inquiry' requires students to be engaged in growth of chemical knowledge. I will now turn to a survey of the literature for a closer examination of cognitive and epistemological accounts of models and modeling and the role of models in chemistry and chemistry education.

Models and Modeling in Cognitive Psychology, Philosophy of Science, Chemistry and Chemistry Education

Models and modeling are important in cognitive psychology (Gentner & Stevens, 1983; Johnston-Laird, 1989), philosophy of science (Black, 1962; Giere, 1991; Hempel, 1965; Machamer & Woody, 1992; Redhead, 1980), chemistry (Suckling et al., 1978; Wilson, 1984), and chemistry education (Carr, 1984; Grosslight, Unger, Jay & Smith, 1991). Models play significant roles in analogical reasoning (Brown & Clement, 1989; Glynn & Duit, 1995), model-based reasoning (Clement, 1991; Reif, 1983), problem-solving (Chi, Feltovich, & Glaser, 1981; Gable & Bunce, 1993; Larkin, 1981), and they are instrumental in summarizing data, making predictions, justifying outcomes and facilitating communication in science. Although considerable research has been carried out on the role of models and modeling within the context of instruction and learning, most studies have concentrated on physics or biology as the science domain (e.g. Clement, 1983, 1989; Giordan, 1990; Glaser & Raghavan, 1995; Stewart, Hafner, Johnson, & Finkel, 1992).

Philosophers of science often situate models as intermediaries between the abstractions of theory and the concrete actions of experiment (Downes, 1993; Redhead, 1980). They examine explanatory power of models (Cartwright, 1983; Woody, 1995) and the relation of models to theories (Giere, 1991). Cognitive psychologists, on the other hand, study the role of models in cognitive development (Johnson-Laird, 1983; White & Frederiksen, 1986) and individuals' model-based reasoning in specific domains such as physics and mathematics (Reif, 1983; Schauble et al., 1991). In general, a model is characterized as a representation between a source and a target (Boulter & Gilbert, 1996a; Duit & Glynn, 1996), the target being an unknown object or phenomenon to be explained, and the source being a familiar object or phenomenon that helps to understand the target.

Cognitive psychological definitions of models which concentrate on *personal* and *subjective* mental models, are often contrasted with anthropological definitions (D'Andrade, 1992; Geertz, 1973; Shore, 1996) which emphasize models as *cultural* and *intersubjective*. Depending on the purpose of the definition, however, models can be characterized and classified in various ways (Mihram, 1972). The purpose of investigating definitions of models in this paper is not to present a case for the nature of models based on how and where - in the mind or in culture - models originate and operate. Selection of exemplar cognitive and epistemological accounts of models is meant to provide consistency with the cognitive development-theory change issue that has been raised earlier in the paper. Furthermore, these accounts are intended to offer guidelines for applying models in educational contexts. In application to chemistry education, descriptions of models in chemistry can be enriched with interdisciplinary perspectives that can inform teaching and learning about what can count as a model. The following section will hence outline: (a) Cognitive and epistemological accounts of models and modeling, (b) models and modeling in chemistry, and (c) models and modeling in chemistry education.

Cognitive and Epistemological Accounts of Models and Modeling

In cognitive psychology, research focus has been on the development of a set of constructs that can be invoked to explain cognitive phenomena ranging from visual perception to story comprehension (Mehler, Walker & Garrett, 1982; Rumelhart, 1980). Mental models (Johnson-Laird, 1983; Norman, 1983; White & Frederiksen, 1986) is one such construct. As Gardner (1987) argues the major accomplishment of cognitive science has been the "clear demonstration of the validity of positing a level of mental representation" (p. 383) such as scripts, schemas and mental models.

In philosophy of science, models are typically perceived as intermediaries between actions of experiment and scientific theory (Black, 1962; Cartwright, 1983; Giere, 1991). While some authors (e.g. Hesse, 1966) emphasize the *properties* shared and not shared between a model and what is modeled, others (e.g. Sellars, 1977) concentrate on the sharing of *relationships* among properties. For instance, in the billiard model for the kinetic theory of gases, the model (the billiard balls) and the modeled (the molecules of gas) may not share physical properties but share the relationship between speed of balls (or molecules) and time to travel a certain distance.

In the following paragraphs, I will exemplify cognitive and epistemological accounts of models in more detail through Bruner's (1966) and Giere's (1991) perspectives. I will then turn to more contemporary arguments such as Gilbert and Boulter's (1997) typologies of models and Woody's (1995) features of models in order to elaborate models further. I will raise the question of whether or not the mentioned categories and features have the same general characteristics at different levels of cognitive functioning. In other words, I want to question the extent to which correspondence between models can be drawn between one level of cognition (e.g. personal) and another (e.g. cultural). Similar questions have been raised in cognitive science, particularly since the development of connectionism (Rumelhart, 1980). The relation of models across different levels of cognition becomes critical in classrooms since classrooms are places that accommodate both personal and cultural cognition (Glaser, 1994).

Bruner's Classification of Models.

Bruner (1966), a cognitive psychologist, identified three types of models: enactive, iconic and symbolic or conceptual. An *enactive* model points to the way in which an individual can translate his or her experience into a model of the world through action. We see an instance of this kind of modeling in the behavior of those scientists who begin tackling a problem by trying to mimic a phenomenon with their hands.

Bruner's second category, which he calls *iconic*, is based on summarizing images. Some models are, in some way, physical representations of their prototypes. Examples include maps and small scale buildings that are constructed to provide data for the design of the full-scale versions. It is common practice to identify a 'model' with 'prototype', something to serve as a standard or to be copied. Kuhn (1962/1970) used the word 'model' in this sense when he discussed networks of achievements that scientific communities acknowledge as providing the foundations for further practice.

Bruner's third type of model, *symbolic* or *conceptual* model, is essentially a mental construct that may range from the simple descriptive to the rigorously analytical, and in which the symbolism may be as varied and loosely defined as a pattern of thought or as precisely specified as an algebraic equation.

Giere's Classification of Models.

Giere (1991), a philosopher of science, proposed three categories of models: scale, analog and theoretical. Giere's notion of *scale* models are similar to Bruner's iconic models in the sense that scale models share similarity of structure with real objects. *Analog* models involve development of a theory of a new system based on similarities between a known system. Analog models can be illustrated by the early attempts to develop a theory of atom from an analogy with the solar system. Giere's third category is *theoretical* models: a kind of system primarily based on language. Theoretical models are created by formulating and arranging statements in order to define a system. For instance, a Newtonian particle system is a theoretical model that consists of the three laws of motion and the law of universal gravitation.

Boulter and Gilbert's Typologies of Models.

Boulter and Gilbert (1996) proposed classification of models based on typologies. Typologies suggest particular models which are representative types and which exemplify groupings. Typologies - taxonomies and partonomies - are derived from psychological accounts on the classification of objects and phenomena at large (Tversky, 1989). Boulter and Gilbert suggest that partonomies of models are based on functional and structural aspects of models, and taxonomies are based on subordinate and superordinate categories in an hierarchical arrangement of models.

Boulter and Gilbert (1996) propose three typologies of models: primary taxonomy, performance partonomy and exemplary taxonomy. *Primary taxonomies* emphasize material or symbolic and static or dynamic features of models. *Performance partonomies* are based on certain aspects of models such as structure or behavior. The focus here is on the particular parts of models that allow the analysis of structural and functional aspects of models. *Exemplary taxonomies* group students' expressed models, models that emerge through the curriculum or teaching models. These taxonomies allow comparisons between classroom models, teacher's models and students' models of particular scientific phenomena.

Woody's Features of Models.

Woody (1995) identified four characteristics of models: approximate, productive, compositional and visual. 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 judgments and criteria driving its construction.

Another characteristic of a model proposed by Woody is that it is *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 sense that we know which entities and relationships can be represented, the model does not similarly hold specifications 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.

I would like to raise the question, at this point, about whether or not the mentioned categories and characteristics of models have the same general features at all levels relevant to cognitive functioning. In other words, how much correspondence is there between models at one level of cognition (e.g. personal) and another (e.g. cultural)? How far can we extend and interpret a cognitive psychological or an epistemological account of models for classroom learning purposes?

As an example for the issue of correspondence of models at different levels of cognition, let us consider the Arrhenius model of acids and bases which will be described in more detail later in the paper. This model can be classified in terms of Bruner's (1966) conceptual or symbolic model since it entails a chemical equation. If the Arrhenius model is specified in a script-like format in the mind of the chemist, does this mean that classroom models of acids and bases should also have a script-like format? Certainly instructional goals would include students' acquisition of an understanding of symbolism associated with the Arrhenius model. However, would the script format be an effective *tool* in classroom teaching and learning? Or would a redefinition and characterization of the

Arrhenius model through, for instance, an iconic model be more effective for the purposes of the classroom?

Gilbert and Boulter (1997) begin to address such questions by differentiating between mental, expressed, consensus and teaching models. *Mental* model is a cognitive representation of an event, object or a phenomenon. *Expressed* model is that version of a mental model that is expressed by an individual through action, speech or writing. *Consensus* model is an expressed model subjected to testing by a social group. The social group can be the scientific or classroom communities which have agreed that a model has some merit relative to some criteria. In the sense that a consensus model is a model negotiated within a community, it is regarded as an extension and modification of personal mental models. A *teaching* model is a specially constructed model used to aid the understanding of a consensus model.

Syntheses of ideas raised so far can provide some guidelines for the implementation of modeling in the classroom. For example, Woody's (1995) characterization of model features can, in principle, apply as criteria through which Gilbert and Boulter's (1997) expressed models are evaluated. For instance, questions can be raised about the approximate and visual representational aspects of models. What does a proposed model of an acid include that is based on evidence generated through classroom experiments? What does it *exclude*? Is the model good based on the criterion that a model is to facilitate visual communication? Such questions can guide the construction of consensus models in the classroom.

The exemplar cognitive psychological and epistemological accounts of models presented in the preceding section: (a) provide a framework for identifying and categorizing models, (b) have the potential for application in educational contexts, (c) are likely to enrich chemical accounts of models for the purposes of classroom learning. In the next section, I will trace the role of models and modeling in chemistry.

Models and Modeling in Chemistry

Chemists (Suckling et al, 1978; Tomasi, 1988; Trindle, 1984) have drawn attention to the significance of models and modeling in chemistry. Models are not only important in chemistry but also they possess a special status in chemistry. It is through modeling the structure and function of matter that chemists *do* chemistry (Erduran & Hotchkiss, 1995). Chemists model the physical and chemical properties of matter in an effort to explain why matter behaves in certain ways. In the case of acid-base chemistry, for instance, physical and chemical properties of acids and bases are explained with Arrhenius, Bronsted-Lowry and Lewis models (Atkins, 1991). The following brief overview of these models will exemplify the role of models in chemistry.

Towards the end of the nineteenth century, Svante Arrhenius classified a compound as acid or base according to its behavior when it is dissolved in water to form an aqueous solution. He suggested that a compound be classified as an 'acid' if it contains hydrogen and releases hydrogen ions, H^+ (see Figure 1). Likewise, a 'base' was defined as a compound that releases hydronium ions, OH^-, in a solution:

* Insert Figure 1 about here *

In Figure 1, H stands for hydrogen; A and B stand for other element(s) in the compounds; and (aq) stands for aqueous.

At the turn of this century, Johannes Bronsted and Thomas Lowry proposed a broader definition of acids and bases where it is possible to speak of substances as intrinsically acids and bases, independent of their behavior in water. The new model was formulated based on observations that substances could behave as acids or bases even when they were not in aqueous solution, as the Arrhenius model required. In Bronsted-Lowry model (see Figure 2), an acid is a hydrogen donor and a base is a hydrogen acceptor. There is no requirement for the presence of water in the medium:

* Insert Figure 2 about here *

The acid-base chemistry took yet another turn when the centrality of hydrogen in both the Arrhenius and Bronsted-Lowry models was challenged. Chemistry, is afterall, concerned more fundamentally with electrons, not hydrogen. Furthermore, the Bronsted-Lowry model did not capture all substances that behave like acids and bases but do not contain hydrogen. Gilbert Lewis formulated yet a broader definition of acid-base behavior. Lewis considered that the crucial attribute of an acid is that it can accept a pair of electrons and a base can donate a pair of electrons (see Figure 3). In Figure 3, : stands for a pair of electrons. In the context of the Lewis model, electron donation results in the formation of a covalent bond between the acid and the base. Lewis hence refocused the definition of acids and bases to something more fundamental about any atom: electrons.

* Insert Figure 3 about here *

What this brief survey of models of acids and bases illustrates is that certain criteria, such as presence or absence of hydrogen in the substance, shaped the evaluation and revision of each model. The process of model development, evaluation and modification is not unique to acid-base chemistry. In chemical kinetics, for instance, the mechanism of chemical change has been explained by various models developed throughout history of chemistry (Justi & Gilbert, in review).

The 'anthropomorphic' model described a chemical change in terms of the readiness of the components to interact with each other. The 'affinity corpuscular' model emphasized the chemical change in terms of atomic affinities. 'First quantitative' model introduced the notion of proportionality of reactants for chemical change to occur. The 'mechanism' model began to outline steps in a chemical reaction. The 'thermodynamics' model drew attention to the role of molecular collision (with sufficient energy) in chemical change. The 'kinetic' model introduced the idea of frequency of collisions of molecules. The 'statistical mechanics' model relied on quantum mechanics and identified a chemical reaction as motion of a point in phase space. The 'transition state' model provided a link between the kinetic and thermodynamic models by merging concepts of concentration and rate.

The role of models in chemistry has been underestimated since the formulation of quantum theory at the turn of the century. There has been a move away from qualitative or descriptive chemistry (which relies on development and revision of chemical models) towards quantum chemistry (which is based on the quantum mechanical theory). Increasingly, chemistry has emerged as a reduced science where chemical models can be explained away by physical theories:

> "In the future, we expect to find an increasing number of situations in which theory will be preferred source of information for aspects of complex chemical systems." (Wasserman & Schaefer, 1986, p. 829)

Atomic and molecular orbitals, formulated through quantum chemistry, have been used to explain chemical structure, bonding and reactivity (Luder, McGuire & Zuffanti, 1943; Nagel, 1961).

Only recently has an opposition to quantum chemistry (van Brakel & Vermeeren, 1981; Zuckermann, 1986) begun to take shape with a call for a renaissance of qualitative chemistry. Underlying the emergent opposition is the argument that quantum chemistry has no new predictive power for chemical reactivity of elements that descriptive chemistry does not already provide (Scerri, 1994b). Rearrangement of the Periodic Table of elements away from the original proposed by Mendeleev and others, for instance, towards one based on electronic configurations first suggested by Niels Bohr yield no new predictions about chemical or physical behavior of elements. Furthermore, no simple relation exists between the electron configuration of the atom and the chemistry of the element under consideration. In summary, there is no evidence to suggest that new physical and chemical behavior of elements can be explained or predicted by quantum theory.

What the preceding discussion demonstrates is that although models have historically been central in the growth of chemical knowledge, in recent years a greater role was granted to quantum theory in chemistry. The purpose of this paper is not to contribute to the philosophical debate surrounding the status of chemical knowledge. This paper is more concerned about aligning chemistry education with the emerging arguments for granting chemistry a distinct epistemology where models play a key role. In the following section I will examine how models and modeling have been perceived in chemistry education.

Models and Modeling in Chemistry Education

There is substantial evidence that children learn and use models from an early age (Schauble et al., 1991; Scott, Driver, Leach, & Millar, 1993). Children's learning of models in the classroom has been promoted on the grounds that models can act as "integrative schemes" (NRC, 1996, p. 117) bringing together students' diverse experiences in science across grades K-12. The Unifying Concepts and Processes Standard of The National Science Education Standards specifies that:

> "Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power. Models help scientists and engineers understand how things work. Models take many forms, including physical objects, plans, mental constructs, mathematical equations and computer simulations" (NRC, 1996, p.117).

Science as Inquiry Standards emphasize the importance of students' understanding of *how* we know what we know in science. Taken together, these standards suggest it is not enough that students have an understanding of models as such. In other words, acquisition of declarative knowledge or conceptual information on models is only one aspect of learning models. Students need also to gain an appreciation of *how* and *why* these models are constructed. What is implied with the latter standard is that students need to develop an understanding of procedural knowledge within a domain of science that employs models.

In light of the mentioned standards, it is important to evaluate how models have been conventionally treated in the chemistry classroom. When we examine the use of chemical models in teaching, we witness several trends that suggest lack of support for students' understanding of models and modeling. First, chemical models have been presented to students as *final* versions of our knowledge of matter: copies of real molecules in contrast to approximate and tentative representations (Grosslight et al., 1991; Weck, 1995). Within the traditional framework of teaching, the motivations, strategies and arguments underlying the development, evaluation and revision of chemical models are overlooked. Classroom teaching typically advances the use of models for conceptual differentiation. For instance, models are used to distinguish weight from density (Smith, Snir & Grosslight, 1992), and temperature from heat (Wiser, 1987).

Second, textbooks often do not make clear distinctions between chemical models (Glynn, Britton, Semrud-Clikeman & Muth, 1989) but rather frequently present inaccurate 'hybrid models' (Justi & Gilbert, in review). Carr (1984) provides the following example which illustrates a common model confusion in textbooks:

> "Since NaOH is a strong base, Na^+ is an extremely weak conjugate acid; therefore, it has no tendency to react with H_2O to form NaOH and H^+ ion." (p. 101)

The first statement is based on the Arrhenius model of acids and bases. The second statement can be interpreted in terms of the Bronsted-Lowry model although the emphasis on ionization is not consistent with this model. When and why a new model is being used, and how this model differs from another model are not typically explicated in textbooks (Carr, 1984).

Third, chemical models have been synonymous with ball-and-stick models which are typically used as visual aids (Grosslight et al., 1991; Leisten, 1994). These 'physical models' have been intended to supplement conceptual information taught, and their use has been justified on Piagetian grounds: that students in concrete operational stages, in particular, need concrete models to understand the structure of molecules (Battino, 1983). The problem with this perspective is threefold:

1. The separation of conceptual information about atoms and molecules from physical models that represent them is inappropriate. Physical models *embody* conceptual information. In fact, their very existence is based on conceptual formulations about atoms and molecules.

2. The focus on chemical models as physical models underestimates the diversity and complexity of models in chemistry. As illustrated earlier, for instance, models of acids and bases are abstract, and each model is accompanied by different sets of premises about what an acid or a base entails.

3. The presumption that students in concrete operational stage *especially* need physical models is simply a weak argument. It is common practice for chemists themselves to use physical models to facilitate their communication and understanding of the structure and function of molecules. What this argument achieves in doing is to stress a deficiency on the part of children's potential to learn.

The fourth trend in the treatment of chemical models in the traditional classroom concerns the shift in emphasis from models to theories since the incorporation of quantum mechanical theories in chemistry. Chemistry and physical science textbooks show a growing tendency to begin with the establishment of theoretical concepts such as the 'atom' (Abraham et al., 1994; Erduran, 1996). Textbooks often fail to stress the approximate nature of atomic orbitals and imply that the solution to all difficult chemical problems ultimately lies in quantum mechanics (Scerri, 1991).

Finally, traditionally chemical knowledge taught in lectures has been complemented by laboratory experimentation which is intended to provide students with the opportunity to experience chemistry as inquiry. Chemical experimentation, however, has rarely been translated in the educational environment as an activity through which models are developed, evaluated and revised. Rather, experimentation is typically implemented as data collection and interpretation. Evidence suggests, however, that explanatory models may not be generated from data obtained in laboratory activities if explicit construction of such models is not encouraged (Schauble et al., 1991).

Given the trends in the way that models have conventionally been utilized in the classroom, it is not surprising that students' experience difficulties with models (Carr, 1984; Gentner & Gentner, 1983). Understanding of chemical models has been characterized in terms of three levels in students' thinking (Grosslight et al., 1991). At the first level, students think of models as toys or copies of reality which may be incomplete because they were intentionally designed as such.

At the second level, models are considered to be consciously produced for a specific purpose, with some aspects of reality being omitted, suppressed or enhanced.

Here, the emphasis is still on reality and the modeling rather than on the ideas represented, as it is the case with the first level understanding. At the third level, a model is seen as being constructed to develop ideas, rather than being a copy of reality. The modeler is active in the modeling process. Few students demonstrate an understanding of chemical models as characterized by the third level. Many students' conceptions of models as representations of reality persist even after explicit instruction on models (Glaser & Raghavan, 1995; Stewart et al., 1991).

It is imperative that more attention is devoted to the effective teaching and learning of chemical models. In particular, omission in the classroom of the heuristics, strategies and criteria that drive knowledge growth, is likely to contribute to chemical illiteracy: a form of alienation where, not fully understanding how knowledge growth occurs in chemistry, students invent mysteries to explain the material world. Concerns have been raised about pseudoscientific interpretations of chemical knowledge (Erduran, 1995) and mystification of chemical practices (Leisten, 1994).

In the classroom, recipe-following continues to be disguised as chemical experimentation - a significant problem often referred to as the 'cookbook problem' (van Keulen, 1995). Chemistry, the science of matter, is not driven by recipes, nor by data collection and interpretation alone. Chemists contribute to the development, evaluation and revision of chemical knowledge. For effective teaching and learning of chemistry, classrooms need to manifest 'what chemists do'. What chemists do is to model the structure and function of matter. The acknowledgment of the importance of modeling in chemistry has contributed to the design of an exemplar curriculum framework, *Acids & Bases Unit*, which begins to address the issues raised so far in this paper. I will illustrate this curriculum framework in the following section.

Nurturing Chemical Modeling in the Classroom: A Curriculum Framework

The *Acids & Bases Unit* is a curriculum framework developed as part of Project SEPIA (Science Education through Portfolio Instruction and Assessment), a middle-school science education research program (Duschl & Gitomer, 1997; Erduran & Duschl, 1998, 1995; Schauble, Glaser, Duschl, Schulze & John, 1994; Smith, 1995). The project broadens the idea of science from its conceptual basis to include: (a) the processes that generate the evidence, and (b) the criteria, rules and standards used to evaluate scientific observations and knowledge claims. In the following paragraphs, I will briefly introduce Project SEPIA and then I will describe the *Acids and Bases Unit* in more detail.

Overall, Project SEPIA specifies epistemological, social and cognitive goals for science teaching and learning, and recommends the following design principles which underlie all SEPIA curriculum frameworks:

1. The topic of investigation in the classroom is an authentic question or problem that has some consequence to the lives of the children. In the case of *Acids & Bases Unit*, the topic is the identification and proper disposal of unknown acids and bases found in the classroom chemistry cabinet. These substances can have hazardous environmental and health consequences if left untreated.

2. Conceptual goals are kept to a limited number so as to facilitate the understanding and adoption of criteria and heuristics with which accuracy and objectivity of knowledge claims can be assessed.

3. Students' understandings are assessed through assignments that, by design, produce a diversity of outcomes. For instance, in the testing of the unknowns, a range of pH indicators are used. Students rate the effectiveness of these indicators relative to the overall task: identification and disposal of the unknown substances. Their ratings are publicly shared and discussed.

4. Assessment of students' products and performances are publicly shared employing a teaching feedback strategy called an 'assessment conversation'. Throughout the unit, the teacher receives information about students' understandings through performances and products. This information is evaluated and in turn helps shape the course of instruction.

5. The depth of student understanding is assessed and communicated employing a portfolio process. Students keep folders of worksheets where experimental evidence is recorded.

The main problem-solving tasks in the *Acids & Bases Unit* are the identification of unknown substances as acids and bases, and the generation of strategies for the proper disposal of these substances (Erduran & Duschl, 1998). The problem-solving tasks necessitate the formulation, evaluation and revision of chemical models that can explain the physical and chemical properties of acids and bases. The unit lasts about 5-6 weeks and initially consists of activities that encourage the generation, refinement and validation of several models (e.g. symbolic, physical, pictorial models), which culminate in the Arrhenius model of acids and bases. Thereafter, a paradigmatic shift (Kuhn, 1962/1970) is reinforced through designed anomalies in data that present the case of substances that register as acids or bases with analytical tools but do not fit the Arrhenius model by chemical composition. The last part of the unit then includes activities that guide the evaluation and modification of the old model and formulation of a new model, the Lewis model of acids and bases that can account for the anomalous data.

By design, *Acids & Bases Unit* is intended to engage students in modeling the structure and function of matter within the context of acids and bases. As students do experiments and gather evidence, they propose models to account for their observations. An ongoing conversation is encouraged in the classroom around the strengths and limitations of the proposed models. Models are evaluated by criteria such as consistency with evidence and explanatory power of the model, which are displayed publicly in the classroom. Other criteria can and do arise within the classroom, and these criteria are assessed and employed if the classroom community can establish a consensus on their effective use.

Acids & Bases Unit is an exemplar curriculum framework where there is a departure from the traditional notions of teaching and learning in chemistry. First, the context is one where students' involvement in growth of knowledge is encouraged. Although there are specified instructional goals, students are provided with opportunities to develop and evaluate knowledge claims. Knowledge of acids and bases is not imposed from the teacher or the textbook but rather generated, evaluated and revised. Second, using assessment as a driving force in the instructional process, allows the teacher to perform an ongoing evaluation of students' understandings, and provide needed feedback. The teacher's role shifts from someone who assigns grades and possesses *the* knowledge, to someone who facilitates and guides the development of knowledge in the classroom. Third, the Unit acknowledges the processes, sequences and strategies of model revision in chemistry, and strives to engage students in contexts which allows students' conceptual change.

Conclusions

We come from a tradition in science instruction which involves handing down of concepts and principles to students without engaging them in the processes of scientific inquiry that make possible the generation of these concepts and principles. Although we see that models constitute one source of students' misconceptions in science (Carr, 1984), rarely do we engage students in the processes of formulation, development, revision and use of chemical models and theories. Students' experimentation in the chemistry laboratory is conventionally based on rote recipe-following, and has been reduced to data collection and interpretation (van Keulen, 1995). In other words, students' experimentation is not representative of scientific inquiry that underlies what chemists do. Educational research suggests, however, that explanatory models may not be generated from data obtained in laboratory activities if explicit construction of such models are not encouraged in the learning environment (Schauble et al., 1991).

In the preceding sections, I have argued that development, evaluation and revision of chemical knowledge through modeling is central to the science of chemistry and should be manifested in chemistry classrooms. Students will be immersed in growth of chemical knowledge when they are provided with the opportunities to develop and use the very criteria, heuristics and strategies that provoke and validate knowledge claims of chemistry.Implementation of growth of scientific knowledge in the learning environment requires a shift in focus from teaching science process skills - such as hypothesizing and experimenting - to a stronger emphasis on students' construction and evaluation of scientific theories, models and explanations. 'Science as inquiry' will be achieved when the problem of knowledge growth is addressed in science classrooms.

Understanding chemical knowledge and its growth has broader social, political and cultural implications. In democratic and industrial societies people and their representatives at large, not only expert chemists, possess the political power to make decisions on issues closely linked to chemical knowledge, such as genetic engineering, waste disposal and drug addiction. Hoffmann's (1995) argument for teaching 'what chemists do' calls for a re-examination of how chemical knowledge is treated in the classroom and how future citizens can best be educated.

$$\underset{\text{Acid}}{\mathrm{HA\,(aq)}} \longrightarrow \mathrm{H^{+}\,(aq)} + \mathrm{A^{-}\,(aq)}$$

$$\underset{\text{Base}}{\mathrm{BOH\,(aq)}} \longrightarrow \mathrm{B^{+}\,(aq)} + \mathrm{OH^{-}\,(aq)}$$

Figure 1. Arrhenius model of acids and bases.

$$\underset{\text{Acid}}{\mathrm{HA\,(aq)}} + \underset{\text{Base}}{\mathrm{H_2O\,(aq)}} \longrightarrow \underset{\text{Acid}}{\mathrm{H_3O^{+}\,(aq)}} + \underset{\text{Base}}{\mathrm{A^{-}\,(aq)}}$$

Figure 2. Bronsted-Lowry model of acids and bases.

$$\underset{\text{Acid}}{\mathrm{H^{+}}} + \underset{\text{Base}}{:\mathrm{O}^{2-}} \longrightarrow \mathrm{O\text{-}H^{-}}$$

Figure 3. Lewis model of acids and bases.

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