Developing 'Philosophic' Understanding: Using History, Model-based Reasoning and Epistemology to Reform Science Education

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I. Introduction

This paper discusses the importance of modeling as used in science and epistemology for developing a scientific mind in upper level science education and preservice teacher education. It seeks to further enhance a curricular approach gaining increased attention in the literature which emphasizes the need for both teachers and students to develop a better understanding of science, one which extends beyond the common narrow focus of mastering domain-specific knowledge to include the *nature of science* (NOS).

The idea of what should constitute a "scientific mind" can be understood in various ways, though the underlying assumption seems to hold such a nature can be categorized. Indeed, the prior question—the unqualified one—as to what comprises the basic nature of "mind" itself is still unknown—if in fact it even *exists*—and here no professional consensus is found. For whether the mind as a cognitive phenomenon is shaped primarily by natural development or by culture, and hence whether it is more appropriately explained by neurophysiology, or by the sub-disciplines of psychology, or by artificial intelligence models, or rather instead by socio-cultural and linguistic theories (or some explanatory amalgam of these), is currently much discussed in the expanding interdisciplinary field of cognitive science (Erneling and Johnson, 2005). How then to go on and properly characterize a "scientific" mind? The skeptic may well reply we are chasing a chimera of our own creation. Moreover, and closely related to our subject of education, "developing a scientific mind" (supposing the entity exists and can be nurtured), can be taken as either ends or means. That is, even a restricted take on "mind" as, for example, encompassing generic scientific thinking (which seems a plausible working hypothesis), can be considered as means for other purposes (e.g. for critical citizenship or global education), or as ends in themselves (e.g. to appreciate how nature and technology function; as aesthetics or cultural literacy, and so on). An evaluation here will, of course, depend upon the *goals* of one's educational programme, especially what ideal of the educated person the programme aims for. This is no easy task. It includes one's *philosophy of education*. We shall forego any such discussion here, only to mention it is implied by the theme at hand and cannot ultimately be avoided. One should consider that a debate over exactly such goals, perhaps not surprisingly, is at the heart of the continuing impasse in science education (Bybee and DeBoer, 1994). Our purpose rather is concerned with how to better create a kind of scientific mind than can currently be had with conventional science education, because of the standpoint on epistemology and history, leaving entirely aside the crucial questions concerning means and ends. This assumes a separation of this order can be made, which is by no means clear.

Our work necessarily builds on literature and previous research in several related fields, such as: studies on conceptual change (Duschl and Hamilton, 1998); the "model-based view" of science as discussed in philosophy of science (Giere, 2004; 1991) and cognitive science (Harré, 2002; Nersessian, 2003; 1995); studies rethinking pre-service teacher training (Tsai, 2002); science education research emphasizing the importance of incorporating meaningful *contexts* in learning (Winchester, 2006; Bloom, 1992) as well as the *nature of science* in instruction (Osborne *et al.*, 2003; McComas *et al.*, 1998); and finally, also arguments put forth by those in the history and philosophy of science reform movement (HPS) which stress the significance of both modeling and the history of science (now recognized by many, including scientists) for proper science comprehension, and hence the need for its inclusion in revised and expanded curricula (Mason and Gilbert, 2004; Matthews, 2007; 1998; Duschl, 1994).

In line with other reform efforts, our work should also be seen as contributing to achieving those objectives as found in the new school science curricular reform documents, like the American *Benchmarks* (AAAS, 1993) and the Canadian *Common Framework* (Council of Ministers, 1997), with their explicit emphasis to include NOS instruction. They form part of a larger request for more fundamental changes in the attitude and approach to science teaching, as accentuated in the U.S. *National Science Foundation Report* (NSF, 1996). The argument has been made that NOS inclusion enhances the educative value by raising the interdisciplinary and cultural dimensions of science courses—since it embeds scientific development in cultural and historical contexts while fostering among students a greater emotional satisfaction for curricular themes (Matthews, 1994). Furthermore, a curricular stress on the inherent but too often neglected epistemological dimension could contribute significantly to a substantive improvement in scientific understanding. First, however, a word about terminology. We follow Osborne *et al.* (2003, p. 717), in distinguishing between the *nature of scientific knowledge* and the broader *nature of science*, and limit our discussion predominately to the former. By the former is meant a more confined perspective on those distinctive features of science concerning its epistemology and ontology, while the latter entails the nature of scientific knowledge but also the *methods* of science along with its *institutions and social practices* (the last dimension is frequently subsumed under the rubric of the "sociology" of science).[1]

We begin with an overview of some familiar problems that currently plague science education at secondary and tertiary levels, though we believe it of value to repeat and summarize the chief ones. Then we proceed to discuss why science education must refocus its objectives, and we begin to offer some solutions as provided by the literature on the model-based view in philosophy of science and cognitive science, HPS reforms and pre-service teacher preparation, to help improve teachers' and students' conceptions of science.

II. Some problems with contemporary science education

i). the conventional wisdom

The need for students to "develop a scientific mind" has not been articulated as an explicit goal *per se* of science education since the last major school curricular reforms in the 1950s and 60s, although one can without much controversy assume that this outcome is generally taken for granted by educators at both precollege and college levels. The

[1] We also acknowledge that any discussion involving the nature of science is contentious given the occasional heated disagreements between scientists, philosophers, historians and sociologists of science, along with sundry cultural critics of science (Gross *et al.,* 1996). Since the Sokal hoax and the "science wars" in the 1990s the internal debate between scientists and certain of their academic adversaries (cultural historians, sociologists and postmodernists) has come to public light and a wider audience (Sokal and Bricmont, 1998). Nonetheless, we maintain along with others that for the purposes of science education some general theses of NOS can be formulated which elicit a large degree of agreement among scientists, philosophers and historians (Osborne *et al*., 2003; McComas and Olson, 1998). A helpful list illustrating the areas of consensus and dissensus among the opposing parties is given by Eflin *et al*., (1999).

conventional wisdom still seems to hold that, ideally, such a mind should be a probable, if not an inevitable result of our contemporary educational system, preoccupied as it is with the mastery of textbook-based formal knowledge (content and processes), stylized laboratory work, and with instruction organized according to the disciplinary structure of the separate sciences. Yet in the past several decades numerous studies in science education research in general, and physics education (PER) and chemical education research (CER) in particular, have established that all three of these components are proven fundamentally inadequate to meet this outcome (McDermott and Redish, 1999; Gilbert *et al.,* 2004). That is, the curriculum remains too narrowly specialized, laboratory work distorts the image of actual scientific inquiry and instruction has chiefly overlooked the psychology and contexts of learning, including accommodating students' prior conceptions which create considerable barriers to comprehending complex and abstract scientific schemes.[2] These findings have assisted in creating a pedagogical gulf between education researchers and many classroom instructors not privy to the research (for whatever reason) as to how science education is perceived and should proceed, and contributes to the conventional outlook on the part of the latter. Certainly the science courses and instructional practices they were exposed to as students in secondary and tertiary institutes, and incomplete teacher preparation programs, have significantly played their part.

ii). decontextualized instruction and curriculum

Yet it can no longer be denied that the requirements for developing a scientific mind have not been satisfactorily met for decades in specialized secondary and first year introductory science courses. The litany of problems associated with conventional science pedagogy is by now well-known: the unpopularity and futility of lecture-based courses (Brouwer *et al*., 1999; Hestenes, 1998); the declining enrollments in postsecondary sciences (Rigden and Tobias, 1991); the ongoing low levels of scientific literacy in the general public (around 10%, according to Miller, 1998); and, more importantly for our purposes here, the central concern that much acquired formal

[2] Indeed some studies suggest students' conceptions of motion, heat, light, electricity, genes, atoms, and many others, are only rarely adjusted or replaced by canonical ones after *traditional* instruction—although it can be admitted that the degree of the tenaciousness varies considerably according to level, subject and the alternative kinds of instructional strategies employed (Wandersee *et al*., 1994).

knowledge remains "inert" in the minds of students. In other words, knowledge attained either through operational definitions, lab work or algorithmic problem-solving is neither well-understood nor transferred and used in other contexts, and is often seen by them as unexciting, highly abstract and irrelevant. Hence learners are often of "two minds" when they leave our classrooms: students, some with several years instruction in the physical and life sciences, and even among those who have successfully obtained high scores on standardized tests, have generally not mastered the conceptual understanding and will typically revert back to "common sense" and Aristotelean-type reasoning of forces, motion and gases, for example, once outside of the "text-test" framework (Gardner, 1991; Mas *et al.*, 1987; Halloun and Hestenes,1985).[3] Targeted studies of improving student learning of domain-specific concepts in the physical sciences (for example, in kinematics or chemical bonding) are now preoccupied to remedy this situation using various approaches, such as: "interactive classrooms", peer collaboration, new "inquiry" techniques; conceptual change strategies; micro-computer based simulations (MBL), and others. These newer reform strategies attempt to properly account for both the qualitative and quantitative requirements of the disciplines, and do justice to how students learn.

While these studies are necessary and important they still suffer some major drawbacks. Here we mention two: they remain myopically focused on key concepts in decontextualized settings—in other words, the knowledge imparted thereby is essentially presented as *ahistorical* and without *context*—precisely because such factors are considered irrelevant; hence (secondly) an explicit discussion of *epistemology* and methodology is disregarded (Lederman, 1998). The trouble with this kind of restricted reform pedagogy is that it basically cuts the student off from the ability to construct meaningful learning and gain a deeper insight not only of the concepts being employed but especially the *nature* and *development* of scientific knowledge. More recent research in PER and CER has begun to value and encompass at least meaningful contexts in curricular topic subjects, which includes the historical, the social and the emotional (Klassen, 2006; Gilbert, 2006; Finkelstein, 2005; Redish, 1999).

[3] "Examples include: F = MA (for use in schools) versus "motion implies force" (for use in the real world); natural selection versus creationism; and the kinetic-molecular theory versus the caloric theory of heat" Wandersee *et al*., 1994, p.190). Not all learning will necessarily result in this kind of unintended "two mind-set" outcome, though it is pervasive. A "mixed-outcome" where the student reconciles the two views in a hybrid is also possible.

iii). neglect of the *nature of science* understanding

In keeping with the problem of decontextualized science education, more serious charges in the past two decades or so have also been leveled at the ubiquitous nature of textbook-dominated science pedagogy at the upper levels. The charge has been made that such a pedagogy overwhelmingly presents an obsolete image of science because it lags decades behind the newer studies in history, philosophy, and sociology of science (Duschl, 1994; Jenkins, 1994). Research has uncovered that among both teachers and students fundamental misconceptions exist (i.e. their *personal* epistemologies) about the *nature of science* (NOS), especially pertaining to their understanding of its epistemology and methodology (Abd-Khalick & Lederman, 2000; Meichstry, 1993; Lederman, 1992). Too many carry on in their mistaken notions about science as a body of knowledge and as a knowledge-generating enterprise: the myth persists that science is governed by an overarching and step-wise "scientific method" (usually understood in simplified Neo-Baconian inductivist terms), which guarantees discoveries and truth about nature (Bauer, 1992); beliefs have taken hold that theoretical knowledge is essentially non-tentative, that "progress" is smooth and linear, and that theories can be "proven"[4]; there is confusion about the crucial terms of science like law, hypothesis, model and theory (McComas *et al.,* 1998); there is little awareness of the precarious nature of cutting edge scientific research and the role of human imagination and creativity in knowledge production. (Which is to say students frequently cannot distinguish between "frontier" and "textbook science"; Bauer, 1992); further, there is basically no attentiveness to the vital difference between the evolutionary and revolutionary developments of scientific concepts and theories; and finally, there is in general little understanding of science as a human cultural enterprise which has shaped and continues to shape the values and identity of society, the nature of technology, and even our very consciousness and destiny**.**

Science teachers**,** especially beginning ones, tend to rely heavily on their textbooks and much of the confusion and mistaken views can be laid at the door of misguided textbook-driven pedagogies, with their hidden (and sometimes not so hidden) "history" and "philosophy": to the quasi- and pseudo-historical writing, and to *naïve*

[4] There also exists the opposite view that "theories" seem to function as mere hypotheses which are typically tentative and straightforwardly "falsified" (e.g. the viewpoint that "evolution is *only* a theory").

realist, inductivist or falsificationist philosophical interpretations of science (Niaz and Rodriguez, 2001; Gallagher, 1991; Selley, 1989).

The science education researcher Norman Lederman (1998) contends that unless NOS teaching is made explicit ("given status equal to that of traditional subject matter") the science literacy of students and citizens will hardly improve, and thereto, we would add, neither can they develop a proper scientific mind-set.[5]

iv). specialization and isolation

Furthermore, the nature of *specialization* invariable produces its own problems and paradoxes. The on-going fragmentation of disciplines into sub-disciplines and their resulting isolation impedes the very ability of students to make connections among important ideas and concepts that bridge disciplines, or attempt to seek answers to problems which transcend specialties. (Students in introductory courses it seems are drowning in specialized content—in a sea of facts, descriptions, laws and equations). Yet these are the kinds of issues and problems that most often personally engage their imagination and interests, and thus give meaning to their quests, and are not normally addressed in their content-saturated science courses: some of which will effect primarily their *thinking* about the world while others could possibly effect their *lives* in one way or another (species extinction; global warming; cloning; viral infections; nuclear weapons and waste; forensics; chemical pollution; alternate energy sources; space and time travel; robotics; etc.) This is, of course, not to diminish the value of task- and discipline-specific investigation and problem-solving which require minute attention to detail, whether in, say, astrophysics, nanotechnology or medical research, only to identify that in order to develop a scientific mind equally requires the cognitive and affective flexibility to move between the part and the whole—a flexibility not usually encouraged or afforded by current curricula and pedagogy. For the vast majority of our science students, however, those who will never become professional scientists or science-based technicians the specialization of disciplines should not be a relevant factor to their learning *of* and *about*

[5] Another critique of textbooks, along a different line but one that targets the essence of instructional practice, is that the organizational structure of a subject is not mirrored in how the subject is learned by the student. In other words, as Dewey (1916, p.220) put it almost a century ago, the logic of a discipline is not synonymous with the psychology of learning. In the light of these patent weaknesses in both the areas of epistemology and psychology, it is astonishing to contemplate why textbook-driven pedagogy is omnipresent and continues to be esteemed.

science—and yet the reality of the organization of their courses at secondary and introductory tertiary levels usually has this curricular impediment already built into it, which should *not* be the case.

III. The need to re-shift the focus of science education

Recent school reform documents continue to emphasize that science education needs to broaden its focus to include not only *what* is known (content and processes of formal knowledge) but equally *how* and *why* it is known. Although in the conventional view the "how"-component is usually understood to be sufficiently broached through laboratory or field work, considerable criticism of "cookbook labs" as staged and closed inquiry, along with the insight that scientific methodology is commonly perceived as narrowly inductive, has now come to seriously undermine this (Hodson, 1996; Hegarty-Hazel, 1990).[6] The "why"-component, understood as discovery, the invention of a theoretical construct (like 'gene' or 'positron'), or the development of a model, together with the reasons why the scientific community has come to accept a currently-held theory, is not generally considered, or if mentioned usually glossed over. There has been overall too little emphasis placed on the role of *explanation* in science. This imbalance in the curricular emphasis in science education can be attributed to undervaluing the epistemology of science while overestimating the efficacy of methodology and content acquisition.

As several authors have noted (Stinner *et al.,* 2003; Monk and Osborne, 1997; Duschl *et al.,* 1990), another way to explain this imbalance is to recognize that both teachers and most common curricula have made an important (and implicit) distinction between the *context of historical discovery (and development)* and the *context of justification*. This misapplied positivist principle in science education has stressed the latter while deemphasizing the former. "In the former, ideas are tentative, if not speculative, and described in a language that is interpretive and figurative, often using new metaphors. Most science teachers view their task as being very much concerned with

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[6] In keeping with our restricted focus on *knowledge* and not *methods* in this paper, we will tend to pass over a discussion about this important dimension of science and the need to reform the nature of "inquiry" in order to help build a scientific mind. Instead, we refer readers to Schwartz *et al*., (2004). In a sense this is an artificial separation, since scientific epistemology is inexorably inter-related with methodology.

the transmission of the products of "the context of epistemological justification"—that is, on the narrow focus of "what we know" rather than "how we know"" (Monk and Osborne, 1997, pp. 406-7). This is among the reasons why scientific knowledge is presented to students as a "finished end product", as condensed and complete, and why they perceive it as static, dry and dogmatic. This is "textbook science" in contrast to exciting and open-ended "frontier science" (Bauer, 1992), or what has alternatively been described as "science-in-the-making" (Sutton, 1996) or "fluid science" (Schwab, 1962). It is primarily at the graduate level that students (and hence only for a small minority) can begin to personally experience the "frontier" or research dimension (at least according to how science education is currently structured), although the media often wet the appetites of the general learner for science with the announcements of breakthroughs happening there. A refocus on epistemology, on model-based reasoning and the historical nature of theory-change could overcome this barrier and begin to give the general science learner also a glimpse into the frontier-dimension of science. Ideally, science instruction should strive to weave together both the contexts of discovery/development and justification.

More problematic still, "textbook science" is preoccupied with promulgating, according to the physicist and historian of science Thomas Kuhn (1970), the reigning theory or prevailing paradigm of the day—with little to no concern about how and why that theory has come to be accepted and established. This forces education into both a *moral* and an *epistemological* dilemma. The student is asked to accept this knowledge on the basis of the authority of the teacher and the text (with whatever slim evidence is presented therein), without really knowing the grounds for the legitimacy of that authority—a type of pedagogical dogmatism. Moreover, the textbook plays the central role in science education of furthering what Kuhn calls "normal science" at the cost of discounting "revolutionary science"—by systematically distorting and disguising the actual historical development of concepts and theories. Yet there is no legitimate didactic reason why textbooks must be myopic (leaving Kuhn's concerns aside; Siegel, 1978) and why the conceptual changes that scientists undergo in revolutions ("paradigm shifts") should be ignored—such important aspects can be brought to light with the inclusion of appropriate historical case studies, according to many HPS reformers (Stinner *et al.,* 2003; Justi, 2000). Indeed, according to studies in cognitive science, Nersessian (2003;

1989) and others maintain there are crucial lessons to be had about science learning. Ultimately such a continued distortion of history and neglect of the epistemology of science does a disservice to our students and to the integrity of the nature of education (Matthews, 1994; Siegel, 1979). Though the truncated focus on specialized knowledge ("what is known") can be seen as a means of *training* the scientific mind it hardly serves the adequate purpose of *educating* it.[7] The call for a re-focus towards clarifying the nature of models and model-use thinking—partly but not exclusively in a historical context—and for preservice teachers to become cognizant of their own images, preconceptions or *mental models* of science, is thus to explicitly emphasize the significance of epistemology for the educative process (Tsai, 2002; Hammer, 1995; Monk, 1995; Arons, 1988).

IV. Models and modeling in science and science education

It should be mentioned that the theme of "developing a scientific mind" has been broached to some extent already in science education research, though not overtly, by those authors investigating different aspects of the theme: studies examining the differences between expert and novice when problem-solving; studies concerned with uncovering teacher's and student's own tacit epistemologies (incl. preconceptions) of science; constructivist influenced studies concerned with alternative conceptions and conceptual change, and thereto, related studies in cognitive science attentive to model-based reasoning. Our focus makes use of some of these research findings in order to suggest ways that preservice science teacher's and student's *epistemologies* (beliefs and mental models) can be made explicit and aligned more properly with an appropriate epistemological perspective of science. Such a perspective should reflect actual scientific development and *explanation*, which is heavily dependent on models and modeling.

For our part, we take it as self-evident that to build a scientific mind requires in large part the ability to *explain* phenomena and *justify* one's explanations. This is exactly where modeling must comes to the fore. Both *explanation* and *argumentation* are taken to

[7] "The textbook as it now exists is necessary but it is not sufficient. The full flavour and excitement of science as a creative process cannot be experienced in a historical and philosophical vacuum" (Brackenridge, 1989, p.80). Nor is it sufficient, according to Rohrlich (1988) and Schwab (1962), for a proper grasp of the scientific enterprise.

be at the epistemic core of scientific reasoning, and the research on the value of modeling in learning science (Matthews, 2007; Gilbert and Boulter, 2000; Gentner and Stevens, 1983), complements the work of those who suggest it directly reinforces critical thinking (Giere, 1991), those who suggest it illustrates historical conceptual revolutions (Nersessian, 2003; 1989), and those who wish to enhance the quality of logical reasoning and argumentation discourse in the science classroom (Osborne *et al.,* 2004). Concerning the various model types used in the sciences, we will deliberately restrict our discussion to the value of *conceptual* models in the physical and life sciences, while leaving aside *statistical or probability* models as commonly used in the social and biomedical sciences. We will also not indulge here in the wider claim offered by some authors that mental modeling is cross-cultural and constitutes the key cognitive processes whereby persons construct and employ knowledge of the real world and so forms, in essence, the basis of human reasoning (Oakhill and Garnham, 1996; Halloun, 1996). We are content to limit ourselves to the observation that models and the act of modeling are fundamental constituents of *scientific* reasoning and practice, and of its body of knowledge. We support the general principle, formulated by philosopher of science Rom Harré (2002, p.54), that "scientific thinking is model making and model using."

It is perhaps prudent to first locate modeling within the wider explanatory framework of science before discussing it directly. An understanding of scientific explanation should encompass fundamentally *three* aspects: insight into the *conceptual structure* and *establishment* of a theory (including the empirical laws it can deduce), the kinds and functions of *models* it contains, and hence, thirdly, the nature of scientific *reasoning*. Scientific explanation in its widest sense is often taken to mean "theorizing" but this is essentially comprised of inferring hypotheses, creatively constructing models and assessing (testing) their individual predictions. A theory is a complex conceptual creation which is (usually) comprised of a *set* of models, each restricted to specific domains intending to capture and abstract a given aspect of reality (ex. Newtonian classical mechanics employs various *particle* models—free particle in uniform motion in the limit of low-velocities; uniformly circulating particle subject to a net centripetal force, etc. Halloun, 1996)[8]. As a rule theories cannot be tested directly, only indirectly through the use or application of their models. From an epistemological perspective models are said to *mediate* between theories and reality. On this view models are *subordinate* to theories, but what they lack in broader explanatory power they make up for in their ability to present immediate testable consequences. (In the normal course of teaching the subject matter of a given theory, instructors should explicate this perspective). Students then, must also come to recognize these three aspects of explanation: first, to understand not only the *conceptual (or semantic) net* of which a given theory is comprised (ex. comparing Medieval to Newtonian mechanics, see figures 2 and 3), and *why* it became established (its "history"), but also, secondly, the kinds of *models* it constructs and how they are employed. Lastly, they need to develop the generic skill of modeling *as* scientific reasoning. This would ideally involve the two processes of the *act* of modeling and *evaluation* of models, both of which are sorely neglected in science pedagogy.

Modeling as a *reasoning tool* is indeed a difficult skill for students to learn (Justi and Gilbert, 2002; Grosslight *et al.,* 1991)—as difficult as it is for them to formulate hypothetico-deductive arguments and inference to the best explanation, two other related reasoning tools (Ladyman, 2002). (The difficulty is compounded by the fact they are rarely given the opportunity to learn about such tools, never mind being able to practice them). Typically, *evaluating* a model in science is taken to mean the critical ability to assess whether the theoretical hypotheses of a model are warranted by the empirical data in terms of their "fit" or match. It is on these critical grounds that a theory (whose model is under scrutiny) can then be judged in general as to its adequacy in explaining the particular phenomena in question (the abstracted "reality"). According to Giere (1991, p.iv): "It is the agreement or disagreement between the data and prediction that provides the basis as to how well a proposed model "fits" the real world" (Figure 1). Exactly this way of *thinking*—the act of modeling and critical assessment of models—must be made explicit for students and to preservice teachers.

[8] "A theory may be thought of as a family of models. Different models are derived from a theory using different idealizations, different simplifying assumptions, and different auxiliary hypotheses. Many different models can be derived from a single theory. For instance, if we assume that there are six planets, which are small point masses, then we get one Newtonian model of the solar system. But if we assume that there are 7 planets, or if we model the Earth as bulging at equator, then we get different Newtonian models of the solar system" (Forster, 2000, p.236).

One important way *assessment* of models can be undertaken is by using an historical approach, by choosing studies of those examples in the past where rival high-level theories have confronted each other. In those rare cases where theories clash (ex. Ptolemaic or Keplerian astronomy; Newtonian or Einsteinian physics; phlogiston or Lavoisier's chemistry; young-earth theories or evolutionary geology, etc.), the particular limits and *defects* of their respective models become sharp. Such instances can serve as an effective teaching strategy to help students discover how knowledge can progress, and thus illuminate for them the precarious nature of how science actually advances—along a "paradigm shift" (Kuhn) or along the lines of progressing or degenerating "research programmes" (Lakatos). Alas, conventional instruction rarely elucidates the conceptual structure of even the successful theory/ paradigm (Newton; Darwin; early quantum theory)[9], and even less so does it take sufficient time, if at all, to study the fascinating historical examples of how science deals with cases of competing theories. And most educational research that does stress the worth of modeling tends in fact to confine itself to underlining that worth for learning the restricted subject domain of a single curricular important theory—Kuhn's "normal science"—as *valuable as this is in itself*. Here assessment is seen as allowing students to review and assess their own *mental* models of the curricular topic at hand (Etkina *et al*., 2006; Harrison and Treagust, 2000).[10]

In the analysis of the function of models in science as well as in science education one needs therefore to discriminate between the "knowledge-justification" framework and the "knowledge-development" framework (referred to above). This distinction is also mirrored in a crude and inaccurate way in Kuhn's two aforementioned distinctive science stages, "normal" and "revolutionary". Regrettably, this is usually not done, not even by those stressing modeling for science education. While Kuhn does us a great service in clarifying the crucial role of modeling in normal science, he says little about its worth for theory change and revolutions. Alternatively, Nersessian (2003; 1992) elaborates the function of model-based reasoning for conceptual discovery and theory change but

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[9] This should not be confused with the more typical instance of explicating a physical theory as fully formalized (i.e. in axiomatized mathematical mode) in advanced courses for majors.

[10] The work of Paul Horwitz and his *Modeling Across the Curriculum Project* should be mentioned as an excellent example of how new software using computer-based modeling simulations can considerably improve students abilities to become active modelers in physics, chemistry and biology.

generally passes over normal science (Gilbert *et al*., 2000).[11] Both of these perspectives need to be taken together, nonetheless, to present us with a fuller epistemological picture of science, which we discuss below, and hence what it can suggest to us about an improved science education.

i). Models and modeling as used in science and for knowledge construction

There are at least *four ways* models have come to be represented in science:

i) material (or scale) models

ii) conceptual (or mental or schematic) models

iii) mathematical models

iv) visual models (graphic and virtual, e.g. computer simulated)

We illustrate these with some examples. *Scale models* still play a role in astronomy and the physical sciences, but to lesser degree than in other fields, like in biology, engineering, architecture and medical science. In the past (history of science) as well as the present, scale models have often performed a dual role in advancing scientific understanding, either to help clarify the nature of a theory and aid investigation or as pedagogical devices in learning the theory. Such a *dual purpose role* needs to be recaptured for science education. From astronomy, the first mathematical science, one traces the earliest use of scale models. The Roman orator Cicero records that Archimedes had built a celestial globe to depict the motion of celestial objects, and the use of armillary spheres continued well into the Renaissance (Peterson, 1993). In modern times a well-known example comes from molecular biology. Watson and Crick's discovery of the structure of DNA was greatly aided by their attempts at building scale models. Moving into the past again, Andreas Vesalius's precise anatomical drawings of the human body, published in 1543 (the same year as Copernicus's ground breaking book) is a good example of how a *visual model* helped revolutionize medicine. In modern day geology visual models played a key role in the scientific community to help overcome the controversy of continental drift and establish plate tectonic theory during the 1960s revolution (Giere, 1996). Having evolved today along with computer graphic technology, they are proving invaluable. *Conceptual* and *mathematical* models, however, are still

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[11] She has, though, emphasized the value of "constructive modeling" for both stages of science (1995).

considered to be of primary importance, and they virtually define the more mathematical sciences. Both are sometimes grouped together as "theoretical" models.

The philosopher of science Malcolm Forster (2000), distinguishes between three levels of theorizing which form a hierarchy: at the top are fully developed (and paradigmatic) *theories* which govern a science; *models* form the middle tier, which allow for the concrete applications of the theory, and *predictive hypotheses* of the model at the lowest tier, that allow/disallow for fitting the model to the data (Figure 1). (He also argues, when considering the contentious question of the *ontology* of theories, that there exists a "trade-off" of truth against predictive accuracy as one moves up the levels. Scientists tend to incline towards instrumentalism with their models but towards realism with their theories)[12]. On Kuhn's view of science "normal science concerns the development of the middle layer—at the level of models. Revolutionary science involves a change of theory at the top" (p. 232). Conventional science education is preoccupied with disseminating the established theories of this stable stage of "normal science", although at least Kuhn openly reinforces the vital role of modeling there. Let us look more closely at this, for it is not only neglected in science education generally but it has been equally undervalued by positivist-influenced philosophy of science until recently.

When Kuhn came under criticism and redefined his vague concept of "paradigm" to mean a "disciplinary matrix" (1970, Postscript), he explicitly included the nature and use of models, albeit used with two separate senses: as a *problem-modeling approach* and as *ontological commitment* on the part of a given scientific community[13]. The first sense refers to exemplary problem solutions or "exemplars" which every student is exposed to, usually from textbook problems and laboratory work[14]. In this practical way the student comes to understand how the prevailing theory operates and ideally, should serve as a kind of critical puzzle-solving template or *conceptual model frameworks* when later tackling actual research problems with unknown outcomes (p. 189). These exemplars as

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[12] The ontological status of models will be further discussed below. Suffice to say that the degree to which models can be interpreted to "approximate truth" in nature (i.e. their realist status) is debated in philosophy of science: Giere's "constructive realism" versus Van Fraassen's "constructive empiricism" (Giere, 2005).
[13] It is not coincidental that his two senses of model are mirrored in his two differing senses of paradigm.
[14] "More than other sorts of components of the disciplinary matrix, differences between sets of exemplars provide the community fine structure. All physicists, for example, begin by learning the same exemplars: problems such as the inclined plane, the conical pendulum, and Keplerian orbits; instruments such as the vernier, the calorimeter, and the Wheatstone bridge" (p.187).

archetype problems are not only shared by the community of professionals, they also help define it (contrasted with other communities), and serve to apprentice the novice into the community's "way of seeing", its approach to problem-solving and reasoning—thereto the significance of textbooks.[15] (Those spear-heading model-based reasoning claim that while the *substance* of such "exemplar" or modeled problem-solving is subject specific and thus non-transferable, the *mode* of reasoning behind it is generic and transferable; Halloun, 1996; Nersessian, 1995)[16]. Kuhn without question correctly saw, contrary to mainstream philosophy of science until the 1980s, that for the sciences "model construction is the engine of normal science, while anomalies provide the fuel" (Forster, 2000, p.237).[17] This process can have epistemic interesting and contradictory consequences—which occasionally occurs as science advances—namely, instances where models have been tested and found to be "true" (better: *empirically adequate*) and therefore *still used*, even though the theory is now known to be false.[18] In other words, after a scientific revolution some models of the archaic paradigm may still be employed (for prediction) although the *meanings* of certain key concepts ("star"; "electron"; "gene") may have undergone a radical transformation.

This brings us to Kuhn's second sense, where he refers to the *ontological* status models have for the community in terms of beliefs and how deep the commitment to them. He argues the loyalty forms a spectrum, at one end are noncommittal "heuristic" models, those that begin as analogies and are easily discarded as research progresses, while at the other extreme end are "ontological" models, those interpreted realistically

[15] In conventional education in the physical sciences this approach has degenerated into algorithmic problem-solving now found to be at the heart of "two mind-set" thinking. Current research using model-based reasoning is attempting in essence to resurrect the intentions of original practice, yet the question remains to what extent this must involve a more intensive and personal apprenticeship-type quality as well.

[16] "Success at constructive modeling requires sufficient domain knowledge. Experts understand the physical and mathematical constraints of a domain sufficiently well for them to function as recipes for constructing models. Initially, students do not have requisite knowledge of the constraints of the domain to construct workable models. And they do not know how to view the exemplars they are presented generically. They do, however, possess the basic cognitive capacities employed in constructive modeling: to make analogies, to create mental simulations, to perform idealization and generic abstraction, and this fact can be taken advantage of and cultivated in the domain of science" (Nersessian, 1995, p. 222).

[17] Some earlier references to modeling were by Hesse (1960s) and Bunge (1970s). See Matthews (2007).

[18] Examples are the use of the earth-centered celestial sphere for use as a navigation device, and Newtonian gravitational theory; Maxwell's classical theory of electromagnetic waves for use in telecommunication.

and firmly entrenched in theory (the dominating paradigm).[19] The abandonment of such a model, which is not done easily, would have serious consequences, and could precipitate a scientific revolution (e.g. the crisis which followed in the wake of the inadequacies of Bohr's "planetary model" of the atom in early quantum theory). It is with this second sense in mind that we now turn to incorporating the history of science and modeling for helping students and preservice teacher's undergo *conceptual change* (a "epistemological shift" as it were) by seeing how Nancy Nersessian (2003; 1992; 1989) values the study of conceptual shifts in theory change (and scientific revolutions), and hence adds weight to the oft neglected "knowledge of discovery/development" component of science.

Nersessian has developed what she calls a cognitive-historical analysis within the "context of discovery" framework in order to uncover the specific mechanisms used by scientists during the generative process of developing new theories. By studying the respective historical documents she has examined in particular Galileo's and Maxwell's use of various conceptual (or mental) models to problem-solve, in the former example to help accompany a revolution in mechanics, in the latter to create a new theory (classical electromagnetism). In Galileo's famous study of free-falling bodies (which helped undermine the qualitative categories of thought in Aristotelean and medieval motion theories and begin the modern transition to our abstract-mathematical conception), he used the *idealized representation* techniques of thought experiments and limiting case analysis. Now while this is well known, Nersessian argues they perform the same cognitive function in that they "facilitate the construction of a mental model that enables manipulation of a representable but actually or practically physically unrealizable situation" (1992, p.57). For Maxwell's case, she shows how the power of analogical and visual ("imagistic") models, some borrowed from Faraday, allowed him to conceptualize and eventually mathematize the electromagnetic field. Nersessian maintains that the use of such abstraction techniques when modeling have a degree of generalisability (as reasoning tools) for instruction and science learning:

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[19] "Though the strength of such commitments varies, with non-trivial consequences, along a spectrum from heuristic to ontological models, all models have similar functions. Among other things they supply the group with preferred or permissible analogies and metaphors. By doing so they help to determine what will be accepted as an explanation and as a puzzle-solution; conversely, they assist in the determination of the roster of unsolved puzzles and the evaluation of the importance of each" (1970, p.184).

These techniques all involve a process of abstracting from phenomena or existing representations and creating a schematic or idealized model to reason with and quantify. These procedures are not formalizable, but can be made explicit and specific applications can be evaluated as good or bad. From my perspective the best way to go about transferring these insights into the pedagogical realm is to start with giving teachers a more realistic sense of the constructive practices of scientists (1992, p.65).

It is entirely in line with the spirit of her suggestion that we are presenting the themes of our paper, but emphasizing both "knowledge frameworks" of science. It is to make explicit what more properly belongs to a scientist's tacit knowledge, and thus, "have scientists preach what they practice" (Nersessian, 1995).

ii). Models, modeling and the history of science in science education

It is instructive to note that she has emphasized how a partial historical analysis can bring "a more realistic sense" to fruition. The traditional view of using the history of science has been one of increasing *motivation* (by showing "the human face" of science, typically using pictures and short biographies) or providing *context* by presenting the background to a scientific idea—although the latter tended to be interpreted mainly in a Whiggish sense (Kuhn's remark about distortion). The general consensus is that both facets of this traditionalism have been failures in helping students develop a proper perspective on the nature of scientific knowledge. This has led current HPS reformers to reinterpret historical context in a more meaningful and authentic manner (Winchester, 2006; Klassen, 2006). There exists the conviction that "the historical process [can] provide a model for the learning activity itself" (Nersessian, 1992, p.54). Some researchers have taken this to mean the need for students to *partially recapitulate* the essence of a physical (or chemical) problem in their original historical context, although the extent or depth of this recapitulation can vary.[20] Others, such as Nersessian and Thagard (1990), maintain that the history of science provides a repository of knowledge about scientific thinking and theory change—about model-type reasoning and how scientists' construct and change their representations, and hence, from which one can glean *analogous processes* on how student's make and modify their theoretical schemas

[20] Stinner (2001), for example, has illustrated that students develop a better understanding of centripetal force and acceleration when the topic is initially broached from the point of view of historical difficulties Newton and Huygens experienced when first studying them (see here also Steinberg *et al.,* 1990), in accordance with the motto that "lesser minds can learn where greater minds had difficulty." This approach in essence seeks to recover, revise and *expand* Kuhn's notion of modeling using problem exemplars.

or frameworks. Regardless of these interpretations, almost all researchers at a minimum have come to recognize the value of foregrounding those specific student misconceptions that parallel historical conceptions in some domains (such as motion, heat, light and gases, as examples), in order to better facilitate conceptual change (Wandersee *et al*., 1994; Hestenes *et al.,* 1992; McCloskey and Kargon, 1988).

The argument has often been made in both cognitive science and science education circles that the conceptual change as experienced by scientists and the community during scientific revolutions is analogous to how students must restructure their knowledge when learning canonical concepts (Duschl and Hamilton, 1998; Duschl and Gitomer, 1991; Carey, 1986).[21] A significant portion of the research has focused on students' intuitive physics ideas in mechanics, and the history and philosophy of science have contributed in different ways in helping us understand student difficulties. It has been pointed out by Nersessian and others that students learning Newtonian mechanics face a similar problem to that which faced Galileo and other pioneers of the early scientific revolution, for they must learn to construct a new conceptual, even abstract mathematical model—one usually at odds with their intuitive or naïve ("Aristotelean") preconceptions—and attempt to match or "fit" this new representation to the physical world. Conceptual change research has shown that students have great difficulty in "restructuring" their previous mental models (especially intuitive physics concepts), with the more canonical ones presented in science classrooms, even when instruction is targeted at this goal.

With the advantage of historical hindsight, Nersessian (1989) offers at least three reasons why this is so when comparing (as a concrete example) how the *conceptual net* of the two competing theories in mechanics (Medieval versus Newtonian) are structured (Figure 2 and 3). First, during a conceptual revolution of this high-level nature, *groups of concepts* are altered because individual terms are interlinked with each other. One notices a three-way change: in kind hierarchies; from properties to relations; and some concepts are altered (deleted or added). For example, the concept of motion has changed form

[21] This represents a major shift in science education (starting in the 1980s) away from the psychology of Piagetian influenced views on student maturational levels to an assimilation of ideas adopted from Kuhnian inspired philosophy of science. It cannot be our purpose here to either describe this shift or to indulge in the rigorous debate which has since arisen because of this shift.

being a process to a state, with repercussions in the hierarchy and how *kinds* of motion have been redefined ("natural" and "local" versus "natural" and "accelerated"). Secondly, there occurs a *meaning variance* for key terms, although the same word occurs. For instance "natural motion" means different things in the two paradigms. Similarly students often employ the same terms but with different meanings. Here the memorization of a definition (as is common in traditionalism) will not suffice for understanding since we can now see that any concept is embedded in a wider web of meaning, in line with Ludwig Wittgenstein's (1958) view of language and how meanings are derived through "family resemblances".[22] Thirdly, such paradigmatic-epistemic shifts involve a change in *ontology*—how scientists and students believe the world to actually exist and behave. In Newtonian physics "rest" and "motion" are both *states* and have the *same* ontological status, whereas for the intuitive "impetus theory" motion—which must have a cause—and rest are of a different order. Similarly, "force" is a relation between bodies, whereas in the archaic impetus view force is a property (or power) inherent to bodies, as many students in fact believe. Research has shown that students need to make the conceptual transition from "motion implies force" to "acceleration implies force." One notices further the alterations of the ideas of space, and while some concepts are dropped ("prime mover") other new ones are added ("inertia"). Thus, how the world was conceived to be constituted has been radically altered, with a congruent shift from a "common sense" mode of thought to *idealization* and abstract-mathematized thinking. The lesson for instruction is that "changing novice representations requires more than rearranging existing elements and more than fitting new facts to existing frameworks. It requires constructing new concepts and working them into a new framework" (Nersessian, 1995, p.205).

We want to be clear about what is being proposed here. It is important to distinguish between history and psychology. We are not of the opinion that all or even most physics learners already have a pre-formed and robust "theory" when learning mechanics which is largely synonymous with the older, fully developed impetus theory,

[22] Hence also a critique of Kuhn's view which held that concepts can be mastered primarily by modeling in "problem exemplars". "Unlike concepts in ordinary language such as 'swan', most science concepts appear together in a complex problem situation. Thus something more is needed for conceptual change than learning similarity and difference relations among problem exemplars" (Nersessian, 2003, p.191).

and which must be replaced wholesale with the Newtonian worldview. We readily acknowledge that the question of the nature of student's intuitive physics knowledge is contentious, as is the view to what extent students need to (wholesale) *replace* or instead (piecewise) *modify* their preconceptions (Reiner *et al.,* 2000; DiSessa, 1993). What can be admitted is that research has indicated most novices *do hold* alternative worldviews which bear striking resemblance to the impetus theory (McCloskey and Kargon, 1988)[23], and that this worldview although not as coherent and fully shaped as the medieval theory nonetheless can be made coherent enough and contains aspects of an alternative ontology (Chi and Slotta, 1993) which seems to be heavily based in notions of material substance (Reiner *et al.,* 2000). So, awareness on the part of the instructor of the historical model can serve as a useful heuristic to partially conceptualize the probable, operating learner's mental model—and perhaps even help coax that model from them. (One must recognize as with any model, its inherent limitations; Strauss, 1988). Equally, Nersessian's observation of a clash of ontologies between novices and experts can be accepted as a reasonable description of one major impediment to canonical theory acceptance and learning. Chi and Slotta (1993) argue that although students' intuitive preconceptions should not be assigned the status of "theory" in the full-blown scientific sense, a better term may be "schema" or "schematic framework" to indicate their structural coherence and robustness.[24] This accords well with our notion of mental models. They can proceed from learner's schemas as they can from scientist's theories. That the inner world of the novice is difficult to study and describe in psychology goes without saying, and yet the historically articulated paradigms, especially during revolutions and theory change, serve as indicators to instructors both of the conceptual complexity and interdependence of meaning contained by any dominant theory as well as the epistemic and ontological task

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[23] "Novices are not merely untutored experts; they see the world with very different eyes. The difference between experts and novices, therefore, cannot simply be represented by describing what the novices lacks . . . In short, the naïf already has a system of beliefs, coherent to varying degrees depending on the individual, and more or less consistently held. The inner logic of the worldview is often shaky and sometimes self-contradictory (as it often is even with trained students) . . ." (1988, p.60).

[24] In this matter see Duschl *et al.* (1990) who contrast the similarities and differences between the comparable notion of "schema" as used in cognitive psychology with the Kuhnian inspired notion of "theory-paradigm" in philosophy of science when attacking the common problem of conceptual change. Nersessian holds that although the kinds of changes are comparable to what happens in revolutions that does not mean we need to uncritically accept Kuhn's views, especially his "gestalt switch" idea.

before them which the novice must "come to see." Modeling as a process used by both experts and novices can become the bridge for that conceptual accommodation.[25]

A useful schematic diagram for instructors when trying to understand the place of individual mental models, and hence personal epistemologies, and their relation to scientific conceptual models, is presented by Greca and Moreira (2001; see Figure 4). One can see in this diagram that the student must be helped to construct or adjust his or her own *personal* mental model in correspondence with that of scientist's *theoretical* model (containing both physical and mathematical models), pertaining to the relevant curricular subject matter. As just discussed, the use of historical models can play an important role here. It can also be applied for facilitating pre-service teachers to amend their preconceptions of the nature of science and instruction. In this case the "physical model" in the diagram would be exchanged with our model-based conception of science. This view of mental modeling can be also aligned with *constructivist* views of learning and instruction. For the interaction between both the teacher's and student's mental models, Figure 5 represents perhaps a more typical classroom scenario. The instructor has the two-fold (complex) task of attempting to ascertain the mental model of the student while aligning his/her own mental model with the proper scientific/curricular model.[26] From this schematic one immediately can see where problems of learning and instruction can arise due to the dynamics of the various mental and conceptual constructions. Neither the teacher's mental model may correspond with the scientific model or the student's

[25] The operative underlying assumption is the "continuum hypothesis", that ordinary and scientific reasoning lie on a spectrum, or that the cognitive practices of scientists are extensions of common human representational thinking when problem-solving. Going in hand with this hypothesis is the view that cognitive conceptual change is parallel for both groups. "However, even if the *kind* of changes are strikingly similar, this does not mean that the *processes* of change will in any way be alike" (Nersessian, 1992, p.51). Of course, it is admitted that in describing both processes as analogous does not in itself *explain* what the underlying (and still unknown) mechanisms are that are responsible for these changes.

[26] To more accurately reflect learning, Figure 5 would need to show the *conceptual* didactic models that necessarily develop from mental models. For simplicity and readability we (also Greca & Moriera) have not added these. We have in fact simply equated mental models *with* conceptual models in our diagram and discussion, which oversimplifies the case: "Conceptual models are devised as tools for the understanding or teaching of physical systems. Mental models are what people really have in their heads. Ideally, there ought to be a direct and simple relationship between the conceptual and the mental model. All too often, however, this is not the case" (Gentner and Stevens, 1983, p.12). A person's mental models are often incomplete and idiosyncratic, and heavily influenced by prior knowledge, attitudes and beliefs, both about the system in question and the reasons for learning about that system.

model, nor may the curricular (textbook) model align fully accurately with the accepted scientific model, especially its historical development.

Recent *Standards* curricular documents have emphasized the value of models:

> 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).

Yet what is often written in such documents does not necessarily translate into classroom practice. An examination of chemical classrooms, here taken as characteristic, can illustrate how the modeling approach has come to be thwarted for several reasons: models have come to be primarily identified with scale models used predominately as visual aids; textbooks often mix models creating confusing "hybrids" (ex. verbal and symbolic statements which mix the Arrhenius and Brønsted-Lowry models of acids and bases without explicating their difference); the tendency for curricular material to shift the emphasis from models to theories; finally, laboratory work has not traditionally structured inquiry around model development and evaluation (Erduran, 2001). What usually results from instruction is a confusion of the terms 'model' and 'theory'.[27]

Certainly one major focus of present curriculum has been getting students to learn the already accomplished models of science, those known to the teacher (ex. the "heart"; DNA; Rutherford's nuclear model; organic chemistry ball-and-stick molecules, etc.) As important as these are, they are usually shown in completed form only and instruction often proceeds with the expectation that rote memory learning will follow presentation. Students, of course, must be exposed to the major models of each science, but the crux of the matter is in the nature of that exposure. Direct instruction does not guarantee they will understand the role such models have in the broader aspect of scientific explanation, nor how the abstraction techniques Nersessian has identified have led to their creation, nor

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[27] "Use of the terms "model" and "theory" within the science curriculum should, therefore, be an indication of the "degree of certainty" with which we hold a particular view. It is quite common in school science to have a realist theory (for explanation) and an instrumentalist model (for prediction) for the same phenomena. Nor is it unknown to have alternative, conflicting instrumental models for different aspects of the same phenomena (e.g., wave and particle models of light). What is confusing for [students] is that the role and status of theories and models are not defined" (Hodson, 1991, p.24).

even why they were initially proposed as predictive hypotheses to tackle an anomaly or help settle a theory dispute during a revolution. Nor especially, their ontological status—whether and when they should be considered as heuristic or realistic, as Kuhn has clarified. Moreover, it usually does not include how such models should be *applied* or even possibly *revised*. Indeed, the revision of models only really makes sense against a background of anomaly (data "mismatch") or historical development—where crucial anomalies come to dislodge an indispensable model (which can be dryly presented as another mere "fact" or alternatively in an exciting story-line format in the "context of development" and "frontier science" framework; Klassen, 2006; Stinner *et al.,* 2003; Justi, 2000). Only when such considerations are brought to the fore does the richness of what modeling involves become apparent to the learner, and indeed, raise awareness of the nature of knowledge and the scientific enterprise.

Yet while some teachers and many experts (scientists) do show an awareness of differing uses and purposes of models, including *types* (scale, visual, conceptual, etc.), this does not appear to be widely shared by their students. Still, even for teachers the process of representing subject-appropriate abstract models (mathematical or conceptual) is accepted as difficult:

> Modelling an object is different from modelling a process. For instance, when modeling a car I just observe it and make a miniature, but when modeling a chemical reaction I have to imagine things I cannot see.
> Modelling a chemical reaction is difficult. I have ideas about substances and the mechanisms by which substances are changed, but I have to think of ways to make my ideas concrete (quoted in Justi and Gilbert, 2002, p.379).

This aspect, though, is seldom recognized by students, the majority of whom consider models to be of the scale model variety and not of the abstract, conceptual type, according to a study by Grosslight *et al*., (1991). They performed interviews with three different groups (7th grade students; 11th grade honor students; experts) to probe and compare their respective epistemologies regarding modeling. Based on these studies they categorized three levels of thinking. At the first level, models are likened to toys and copies of reality, with some distinction between copy and reality due to design. Yet students at this level (most 7th graders) do not distinguish between the idea or purpose (behind the model) and the model or even the data to support or refute it. At level two (11^{th} grade students), such a distinction does begin to take shape although the focus remains on the reality modeled, not the ideas represented. Hence, tests are considered confined to the workability of the model and not the viability of underlying concepts. Models serve primarily as communication tools and not ways to test and develop ideas. Few students attained the third (expert) level of model understanding, characterized by factors such as knowing that models are constructed primarily to aid conceptual development which can be manipulated and tested, moreso than copies of reality (the *explanation* and *assessment* roles in science) and that modelers have an active role in the process. In sum, considering the nature of conventional pedagogy these results hardly come as a surprise.

> If a student is successfully to learn a scientific/curricular model, that person must have: an understanding of scientists' view of the nature of 'model'; suitable experience of the phenomena that is being represented; knowledge of *why* the model was originally constructed and why it has to be learned; an understanding of how analogies operate . . . A necessary condition for such learning is that the teacher is him/herself competent in all these aspects of modelling (our italics; Justi and Gilbert, 2002, p.384).

The paper has so far discussed and clarified the nature of models in science and how history can contribute to the 'why' of model construction. We now turn to the 'necessary condition' just mentioned. To begin to make inroads into transforming science education more along lines commensurate with scientific thinking and practice requires as a first step a renewed emphasis on preservice science teacher epistemology.

V. *Model-based science, epistemology and teacher education*

Science teacher education has gained attention in the literature over the last several decades as awareness grows about the complex connection between teachers' understanding and views about science and the pedagogical practices enacted in classrooms. Numerous studies regarding the preparation of teachers have resulted from reform documents which have called for the improvement of the attitudes, understanding and interest in science across all grade levels (AAAS, 1993, NSTA, 1982). In most studies the attempt is to understand the kinds of experiences and practices that enhance science teachers' pedagogical practices in science with the aim to improve overall classroom experiences. These studies range from examining the role of guided inquiries (Furtak, 2005), using constructivist perspectives in curriculum design (Appleton, 1989), content knowledge as a basis for pedagogy (Shulman, 1986), developing teachers' understanding of the *nature of science* (Abd-El-Khalick & Lederman, 2000)**,** to the relationship between teaching and epistemological beliefs (Tsai, 2002). The studies indicate that initiating change in science education rests on addressing teacher preparation practices as foundations for future professional growth. It is generally accepted that teachers form their core beliefs and pedagogy during teacher training programs.

In the following sub-sections, we continue to develop our thesis that a model-based approach results in more authentic and epistemologically sound learning on the part of students and we further consider that teachers largely determine the kinds of approaches used in teaching and learning science. Given our strong belief in a model-based approach, we explore practical, philosophical and epistemological implications for teacher education.

i). Mental models and epistemologies

Before proceeding, it is important to clarify our terms. The case thus far suggests mental models (conceptual, visual, mathematical, and material) are cognitive constructs that reflect epistemology of science. Models function, as explained earlier, to illustrate the "inner workings" of scientific processes—enhanced by an historical approach—and explicit deconstruction by students and teachers. Mental models, consequently, represent a *cognitive dimension* of epistemology of science – the result of processes, skills and reasoning inherent in the scientific enterprise. Hence, we have emphasized the importance of mental models as representative of *some* dimensions of epistemology. However, as we continue to elaborate on issues of science education from a pedagogical perspective, we acknowledge that a broader conception of epistemology needs to be presented. In subsequent sub-sections, we introduce teachers' epistemologies as including teachers' own views of science and their understandings of the "inner workings" of science (processes and skills) in addition to their cognitive models. A teachers' epistemology is essentially the humanistic manifestation of the cognitive dimensions of science – one holds a view of science or understands its inner workings based on cognition about mental models while the same can be said about the reverse situation. Our argument continues to develop this idea that epistemology, while thus far cognitively examined, is broader and includes affective and attitudinal dimensions when applied to teachers and students in classroom contexts and that acknowledging these is key to science education.

ii). Teachers' epistemology and the images they hold of science

A consistent theme in literature on science education is the relationship between the image of science held by teachers and the kind of science education experienced by students. Michael Matthews (1994) refers to teachers' images of science as their epistemology of science suggesting this significantly affects the manner in which science is taught. In *Science teaching: The role of history and philosophy of science,* he states,

> all science curricula contain views about nature of science: Images of science that influence what is included in curriculum, how material is taught and how curriculum is assessed. The image of science held by curriculum framers sets the tone of the curriculum, and the image of science held by teachers influences how curriculum is taught and assessed. When spelled out, these images of science become statements about nature of science, or about epistemology of science (p. 37).

Over the years, science education has come under attack for creating images of science for students that that do little to consider or reflect science's epistemology. A majority of classroom teaching seems to perpetuate what Bauer (1992) calls the "myths" of science**:** key among them is the view that science consists of fixed truths about the world arrived at objectively by a universal, set method. Science amounts to an accumulation of end products of an infallible process collated and transmitted to students in classrooms. Such conceptions, further perpetuated in textbooks, rarely reveal activities of "frontier science" – when science knowledge develops by processes of discovery, inquiry and experimentation as more authentic reflections of its epistemology. Teacher education, and specifically that of science teachers, lies at the heart of this issue of *images* their students develop about science.

Much of the challenge of science education rests in this fundamental concern: how science is presented, illustrated, explained and articulated depends on how the teacher has made "sense" of science knowledge for him/herself. Given the arguments thus far, it is reasonable to assume that a model-based view of science must be held and valued by teachers in order for students to experience such approaches in their science education – curriculum design and delivery becomes an *extension* of teachers' conceptual and philosophical image of science. Let us take for example, conceptual and visual models as two representations of scientific knowledge. Students, in classic lecture-style and textbook-based pedagogy might experience a description of atomic bonding as *the* conception of particle interaction. Contrarily, teachers who introduce students to the various 'stages' of development of this model of atomic bonding engage students in the scientific enterprise. Students are made privy to the 'inner workings' of how the teacher has made sense of the model while recognizing this is epistemologically more accurate to the processes of science. In a model-based approach, teachers are inclined to use historical examples of how atomic models were modified over time in consideration of new evidence and how even current conceptions are probabilistic in nature – that bonding processes rely on conjectures of the nature and position of particles. It is this kind of 'tentativeness' of our understanding of the natural world that is lost in textbook science, according to Bauer. In contrast, it is possible in a model-based approach to encourage students to visualize the 'invisible', to conceptualize the numerous phenomena that are not apparent to the human eye. This process of visualizing, constructing and selecting physical representations of atoms requires students to infer from written explanations and schematic diagrams in textbooks an authentic model of the phenomena. We suggest, then, that teachers present models to illustrate collectively many aspects of the nature, history and philosophy of science. Indeed, the task for teacher education is to help teachers reflect on their own processes of 'making sense' of models with the aim to design curriculum that mirrors such processes *with* their students.

The image of science held by teachers is predicated on two fundamental principles: their understanding of the *nature of science* (NOS) and the degree to which they understand the philosophical basis to developing scientific knowledge (Hodson, 1988; Lederman, 1992; Matthews, 1994). In the former case, NOS is considered an important and fundamental aim of science education. This is indicated in major reform documents of the 1980s to 1990s which reflect the importance of NOS in science instruction (as was mentioned) *as well as* the call for explicit treatment of NOS in preservice teacher education. In accepting a 'NOS-rich' approach in teaching science requires teachers to value NOS as a basis for curriculum reform and development. NOS, or the epistemology of science according to Lederman (1992), creates opportunities for science to be presented as tentative, socially negotiated, subjectively influenced and empirically based (Lederman, 1992; also Matthews, 1994; NSTA, 1982). Such an approach implies that teachers will engage students in the processes, skills and attitudes inherent in the *development* of scientific knowledge and that such engagement is cursory to developing a more authentic understanding of science.

Recently, numerous studies have suggested an *explicit-and-reflective approach* (Tsai, 2002; Abd-El-Khalick & Lederman, 2000) in surfacing the embedded dimensions of NOS with preservice teachers. Teachers conduct experiments, discuss their thinking processes, write reflectively about the nature of their learning during these experiments and discuss the value of such experiences in collaborative dialogues, all examples which aim to make NOS explicit. Such practices in preservice teacher education endeavour to raise teachers' own understanding of NOS as well as to get at the deeper philosophical underpinnings of the scientific enterprise.

iii). A philosophically valid curriculum

Hodson (1991; 1988) makes a significant contribution to science education in his call for a more "philosophically valid curriculum" in which he renders a curriculum inert if it does not consider the following foundational questions: What is the role and ontological status of scientific theory?; how are theories related to models?; how is scientific knowledge validated and disseminated by the scientific community?; what are the methods of science? Answers to these questions, he argues, are not to be sorted out *prior* to engagement with students – rather such questions ought to constitute the nature of dialogue about science *with* students. One particular illustration of such an approach would be to introduce students to the dynamic nature of the relationship between science practice (methods), scientific theory (and its models), and the physical world. The notion that there exist differences between scientific enquiries – that there is a subject-specificity to the kinds of questions, the nature of evidences and the utilization of theoretical structures is one that ought to characterize how different concepts are approached with students. Subsequently, students understand that an inquiry about the behaviour of light, for example, ought to suggest questions about how light travels through various media, the theories utilizing models of light as particle or wave, and why such information is important to ascertain. These questions drive knowledge construction about light while surfacing, in an explicit way, the processes of 'finding out' what constitutes the nature of light. Critics might suggest that a curriculum that is slowed down to reveal the implicit basis of knowledge construction and development takes too long, renders the curriculum as overly emphasizing processes and forsaking understanding of accepted theories in science. On the contrary, such emphasis determines whether students *even develop* such theoretical understanding. A philosophically valid curriculum supports the view that understanding science depends on how well science processes are explicated with and experienced by students.

iv). Philosophy of science and philosophy of teaching

In purporting a model-based approach, we argue for a philosophically more valid curriculum. The basis for understanding the different kinds of models we outlined earlier, presenting them and utilizing them to propel science knowledge forward require an implicit understanding of the nature of science and an explicit focus on nature of science through both historical and philosophical approaches in the curriculum. HPS, rather than seen as mere "add ons", are considered as curricular frameworks to guide science instruction (Stinner *et al*., 2003; Monk and Osborne, 1997; Hodson, 1988). The challenge remains in preparing teachers to teach using these approaches, recognize them as pedagogically sound and valuable and consistent with aims of science education.

Mellado *et al*. (2005), suggest that one way of directly infusing philosophy of science into teacher preparation is to draw analogous connections between major science philosophies (of Popper, Kuhn, Lakatos, etc.) and teaching philosophies. In one circumstance, Popper's theory of falsification is used to demonstrate how teacher's actions and beliefs can change when they are dissatisfied with conceptions of their practice. Additional analogies are drawn between Lakatos' "research programmes", which identify core theories resistant to change, and teachers' beliefs and practices that also remain unchanged over time. The authors contend this to be an "eclectic" approach but one that raises a critical point in teacher education: teaching practices ought to be *epistemologically grounded.* The potential here is to view science and teaching as *overlapping epistemologies*. The philosophies become mutually dependant by which the manner of instruction emerges out of the 'inner workings' of the content. Specifically, the philosophical basis of science, its nature, can determine the approach taken in teaching science. In an epistemologically grounded learning activity, students encounter the tentative and imperfect models that arise from various processes of falsifying, observing anomalies and weighing existing evidence. Attending to the 'sub-structure' and inner processes of science, it can be argued, encourage the development of sound science pedagogy.

v). Teachers' epistemology and beliefs about science

Whether one's science teaching philosophy is or ought to be solely hinged on major science philosophies is not being argued here. Rather, it is a suggestion that one can consider the *philosophies* of science as one of several frameworks for model-based approach *for instruction*. Clearly, the call to consider epistemology as a basis for curriculum development warrants an examination of teachers' beliefs about science, teaching and learning. Tsai (2002) conducted a study with preservice teachers and found that teachers' beliefs about science were often consistent with their beliefs of teaching and learning: teachers who held a constructivist view of science were most likely to hold a constructivist belief about teaching and learning; alternatively, a traditional (textbook, intact knowledge) perception of science resulted in traditional teache**r-**centered instructional beliefs. Tsai referred to consistency in beliefs as "nested epistemologies" and contended that while teachers may hold particularly sophisticated views of science, until they are explicitly asked to consider how these views are related to their beliefs of teaching and learning, there is often little 'transfer' between teachers' epistemology (view of science) and their pedagogical practices. Further, as teachers become more experienced, there epistemologies become more nested, whether all aligned as either traditional or constructivist. Interestingly, junior teachers (who have less than 3 years experience) tended towards constructivist-aligned beliefs, suggesting some influence on the part of their teacher education programs towards more interactive, generative learning experiences.

Yet, even where teachers' beliefs and views of science may be sophisticated and authentic to its nature, the resulting classroom practice often fails to reflect such teachers' epistemologies (Abd-El-Khalick *et al.*, 1998). The *chasm* between epistemology and practice is further enhanced by rote presentation of material in textbooks and curricular print resources. Textbooks are filled with formal knowledge content, which show limited sophistication of scientific processes and ideas, and are indeed often chosen for their simplicity in describing concepts. Another contributor to this chasm is the apparent lack of attention given to history and philosophy of science in mandated curriculum. Interdisciplinary teaching is often regarded as an "add on" to curriculum rather than as means for developing more robust science understanding. Numerous other administrative conditions (or institutional inertia) limit teachers' ability to reform curriculum ranging from budgetary constraints to philosophical difference within departments and staffs. We acknowledge that *external factors* are well beyond the scope of what we can offer here in terms of the arguments, but it is worth acknowledging the challenges teachers individually and collectively face when confronting their views of science in real classroom practices.

The result of such investigations further suggests an important, yet often overlooked dimension of teacher education – that prospective teachers need opportunities to dialogue about and deliberate personally held beliefs and personal epistemologies with other future teachers (Tsai, 2002) within subject disciplines. It can be hypothesized that nested epistemologies may be discipline-dependant, in which case beliefs about teaching, learning and science need to be treated as somewhat distinct from beliefs about teaching, for instance, history. Although this claim remains open to debate, it does raise the importance of addressing coherence between pedagogical (teaching and learning) practices and epistemology of science.

vi). Teachers as 'modelers'

We return to our earlier elaboration of the function of models within the wider explanatory framework of science. Scientific explanation depends on several dimensions mentioned previously but in respect to teacher education, we focus on the kinds and functions of models in constructing scientific understanding. We have asserted that building a scientific mind encompasses learners engaging in the processes of constructing, deconstructing and assessing models. Given this, teachers' views of science must include substantive understanding of model-based reasoning and they must develop ways in which to convey the *idea* of models as salient dimensions of scientific thinking. When we call for students to engage in the act of modeling and the evaluation of models as part of scientific reasoning, it assumes that teachers are capable of structuring learning scenarios that allow for these kinds of activities. Germane to this discussion is that teachers themselves must be 'modelers' – performing experiments alongside students and assist students in surfacing insights from experiments that help construct new models and/or refine existing ones. Models can be utilized as *pedagogical tools* for addressing misconceptions and explicating the role of data, hypotheses, laws and theories. In time, as students begin understanding the role of evidence, observation and how these articulate with student preconceptions of the phenomena, the opportunity arises to negotiate students' cognitive schema with those presented by teachers. The potential exists for teachers' epistemologies and students' epistemologies to emerge out of the 'modeling' process as yet another form of *overlapping epistemologies* – those of students and teachers. Further, finding similarities and differences in schemata between students and teachers and amongst students themselves seems not only pedagogically favourable, it more authentically reflects science as a social and knowledge –generating enterprise.

vii). Science content knowledge and pedagogy

A discussion about aligning teaching pedagogy with epistemology is incomplete without briefly considering Lee Shulman's (1986) *Pedagogical Content Knowledge* (PCK). Shulman bases his argument on the poor attention given to the evident relationship and dependence between content and pedagogy, what he terms a "missing paradigm" in the education of teachers. Shulman states, "the key to distinguishing the knowledge base of teaching lies at the intersection of content and pedagogy" (p. 15). He delineates *three categories* of content knowledge: subject matter content knowledge, pedagogical content knowledge and curricular knowledge. *Subject matter knowledge* generally equates to our scientific models – the structure of science knowledge and conditions (reasons) for such knowledge to be regarded as valid. Here, we have further argued that historical attention serves well in revealing the development of science's contemporary models. In science education, this equates to teachers designing learning activities to engage students in the processes, skills and attitudes of science – to *enact* the nature of science in the classroom by conducting inquiries, explaining the historical development of models and theories, and to raise philosophical questions to *justify* ideas. The second category, *pedagogical content knowledge* refers to the "most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others" (p. 9, 1986). Relating to our earlier assertions, models also function as pedagogical representations (Shulman's illustrations, examples and analogies) that can be utilized by teachers to elaborate and explain science in comprehensible ways. This involves not only the teacher understanding the content in itself, but understanding that how it can be reworked into other representational forms without forsaking the integrity of the content structure. Indeed, the representational forms are akin to our types of models and, as Shulman suggests, these function well as pedagogical prompts – teacher generate their methods by *drawing them out of* the content structures. Finally, *curricular content*, according to Shulman, refers to utilizing teaching resources, textbooks and technologies effectively to aid the pedagogical representations developed in teaching the content. Salient to this point is that teachers be aware of and develop comfort with using a variety of materials to represent content while understanding which materials work best to represent particular content structures. He further suggests that teachers be aware of the curricular materials used in different courses so as to create connections for students across content areas.

We argue that Shulman's notion of content and pedagogy being interrelated can be appropriately considered as *overlapping epistemologies*. Supposing that pedagogy is a function of teachers' epistemologies and content is the epistemology of science, then Shulman's descriptions of content knowledge support our case for models and model based reasoning as pedagogical tools. The practical implications are straightforward in one sense: teachers' practices must explicitly and actively reflect the development and representation of scientific models inherent in the epistemology of science. In addition, teacher preparation requires that teachers understand these forms of content knowledge in efforts to enhance science teaching and learning in the classroom.

Conclusion

The question then is whether current practices, while increasingly informed by many of the ideas suggested by us in this paper, are sufficient to achieve a more model-based approach in science teaching. In making the case, several considerations are necessary. First, it is important to acknowledge the negative impact of poor representation of nature, philosophy and history of science in both textual/curricular materials and in teaching practices. This largely contributes to issues such as diminished appreciation for, engagement in, and understanding about science. Second, historical and philosophical analysis helps to bring to the fore the model-based nature of science. As earlier described in detail, the four kinds of models create a reasonable and sound basis for creating interesting science activities for students while simultaneously raising criticism of the narrow scope of content presented in textbooks. Students get a sense of the 'story' behind the theory. Further, recognizing the model-based nature of science suggests a view of science that is more epistemologically aligned – a view that encompasses knowing the nature of science as an integral part of understanding science. In order to develop models and utilize them, students potentially engage in processes and skills of science such as creatively using their imagination, weighing evidence, making predictions and collaborating with peers – all dimensions of the nature of science. Third, such an approach is predicated on teachers holding value in teaching science as model-based and holding a view of science as complex and sophisticated in nature. Fourth, aligning teachers' beliefs and images of science with their practices of teaching and learning is fundamental to generating authentic experiences for students, including the development and assessment of scientific models. Finally, teacher education must provide appropriate contexts to develop teachers' epistemologies is such ways and to practice teaching that validly reflects their epistemologies with the aim to better align their beliefs with practices. Integral to this process of developing *epistemologically-grounded* pedagogy is including opportunities to dialogue, reflect and refine personal epistemologies with other prospective teachers.

In summary, the case we make is straightforward: improving understanding in science requires understanding, constructing and interacting with the various models of scientific phenomena in the context of science classrooms. We have extended this premise to suggest that not only students' understanding of science improves but that teaching and learning is enhanced when teachers accept a model-based approach as one foundation for their pedagogy. Our argument is predicated on the notion that models (whether material, mathematical, conceptual or visual) and the act of modeling function both to illustrate salient aspects of theories and to assist in learning about the theories – they act as pedagogical tools. Further, this ability to recognize the model-based structure of scientific explanation depends on teachers engaging students' schematic frameworks, their reasoning capacities and their processes of inquiry. In effect, models, utilized as pedagogical tools, help to clarify students' preconceptions or existing cognitive schema and simultaneously act as 'launching points' for further analysis and inquiry. Of importance is that this process of comparing students' own mental models with existing scientific models encourages numerous scientific thinking processes such as predicting and inferring. We suggest that an improved education is one in which science's model-based nature is explicitly addressed and students' schematic frameworks are engaged in deciphering, modifying and enhancing these models. Anything less, we contend, is a misrepresentation of the history, philosophy and the nature of science.

Science teacher education can be conceptualized as a collection of *overlapping epistemologies*: a teacher's epistemology with epistemology of science, students' epistemologies with epistemology of science and a teacher's epistemology with students' epistemologies. We present such constructs as points for further research and continued analysis, although we acknowledge the already large body of work to date in the area of students' views, attitudes and beliefs of science, but especially regarding their *alternate conceptions*. Clearly, the recent trend to examine teachers' views, attitudes and beliefs (epistemologies) is evidence that *all* epistemologies involved in the classroom (student, teacher, subject) need to be explored for science education to advance. We encourage further discussion about the aims and methods of teacher education in articulating epistemology and offer the following questions for continued inquiry: what is the nature of the relationships between *overlapping epistemologies*?; how are epistemologies made explicit in classrooms?; what circumstances cause students (or teachers) to confront their epistemologies?; what implications does understanding the epistemology of science have on students' and teachers' epistemologies?; how do students (or teachers) convey their epistemologies explicitly? Indeed, it is the task of teacher education to delve deeply into such matters and we suggest the outcomes contribute positively to understanding how to improve science education.

We suggest not only a call for reform in science curriculum development, we contend that reforms are equally necessary in preparation of future science teachers. Perhaps, as we are hopeful that the aims of reform documents such as Project 2061 come to fruition sooner than later, science education will shift from teachers 'doing' and 'explaining' science to students towards students 'doing' and explaining science to teachers. Such a shift is an admirable aim of science education and one that we believe begins in teacher education.

FIGURE 1: SCIENTIFIC REASONING SCHEMATIC (From *Understanding Scientific Reasoning* 3rd edition by R. Giere, 1991, p. 39. Reprinted with permission of Wadsworth, a division of Thomson Learning: www.thomsonrights.com. Fax 800 730-2215)

A flow chart corresponding to the program for analyzing reports of scientific episodes involving theoretical hypotheses.

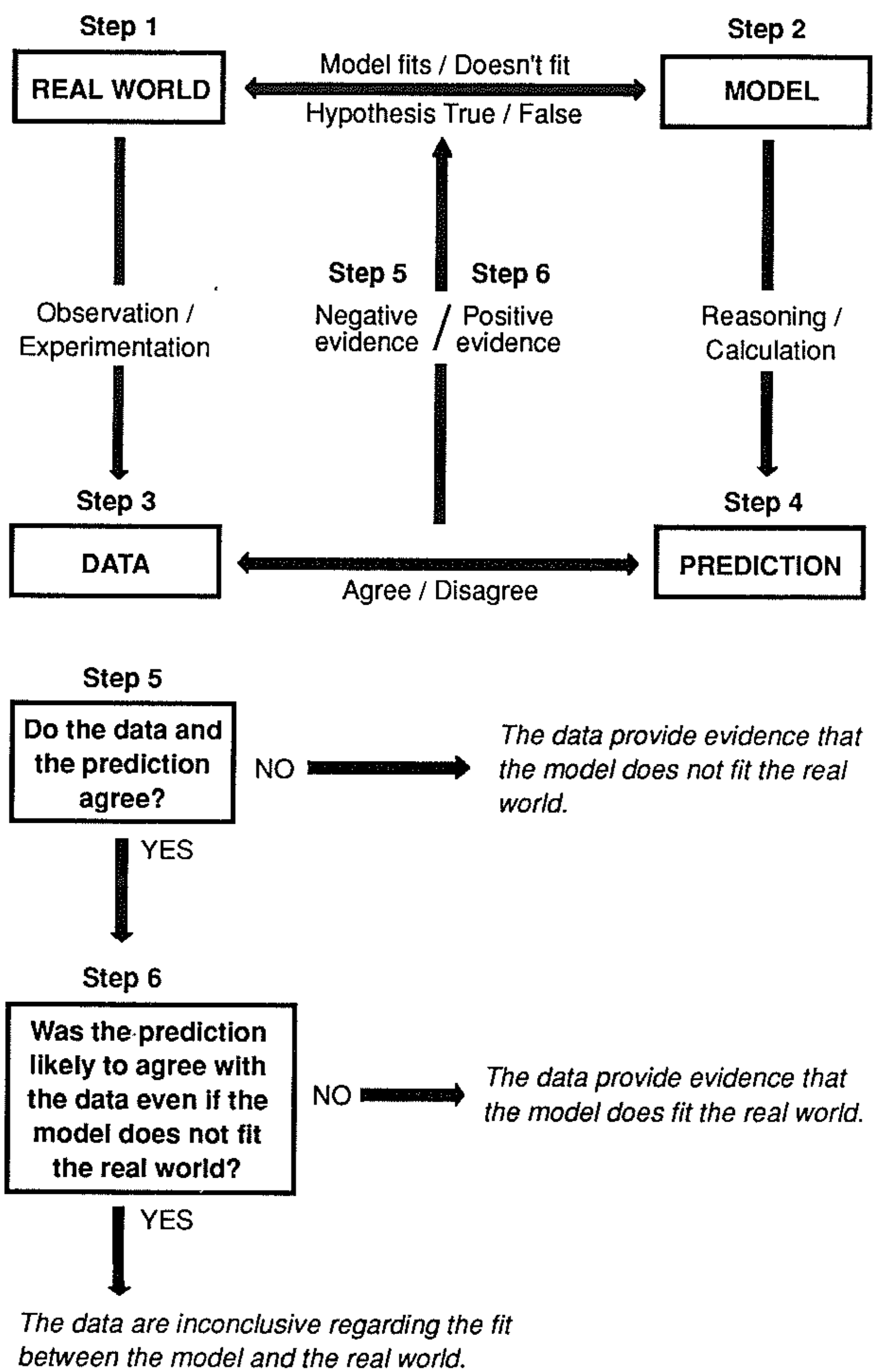
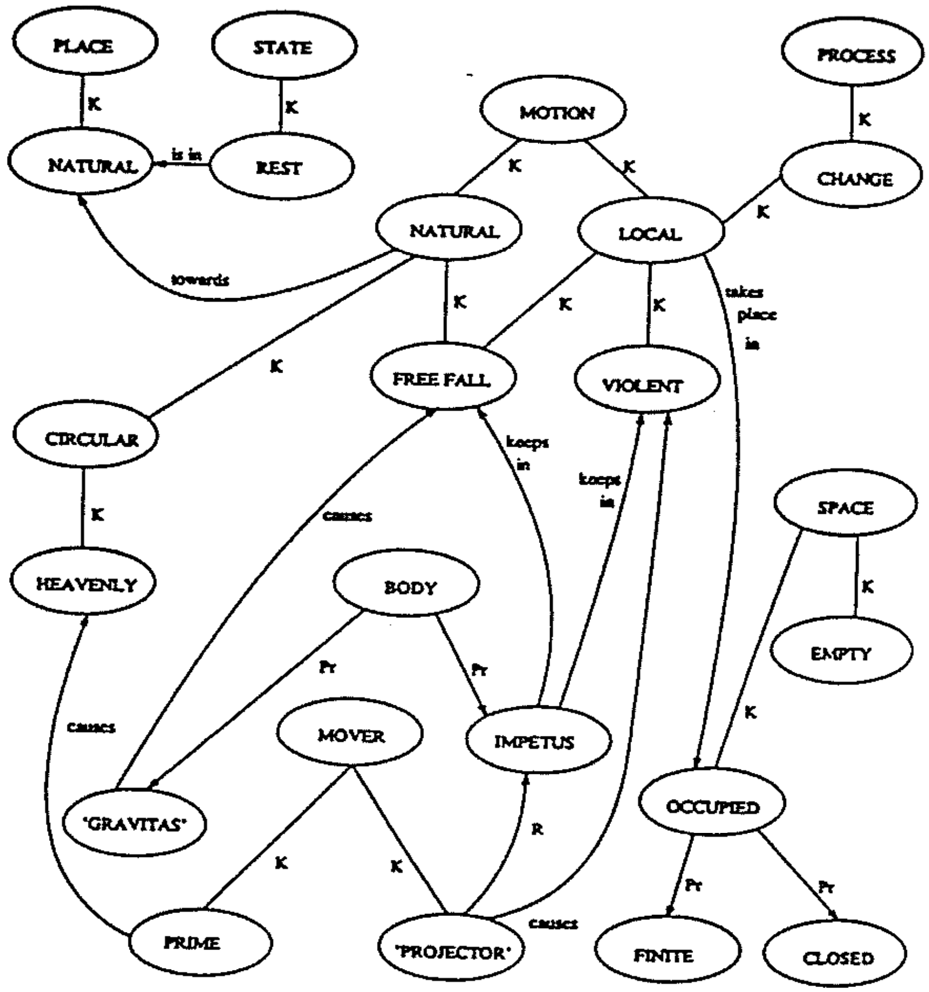
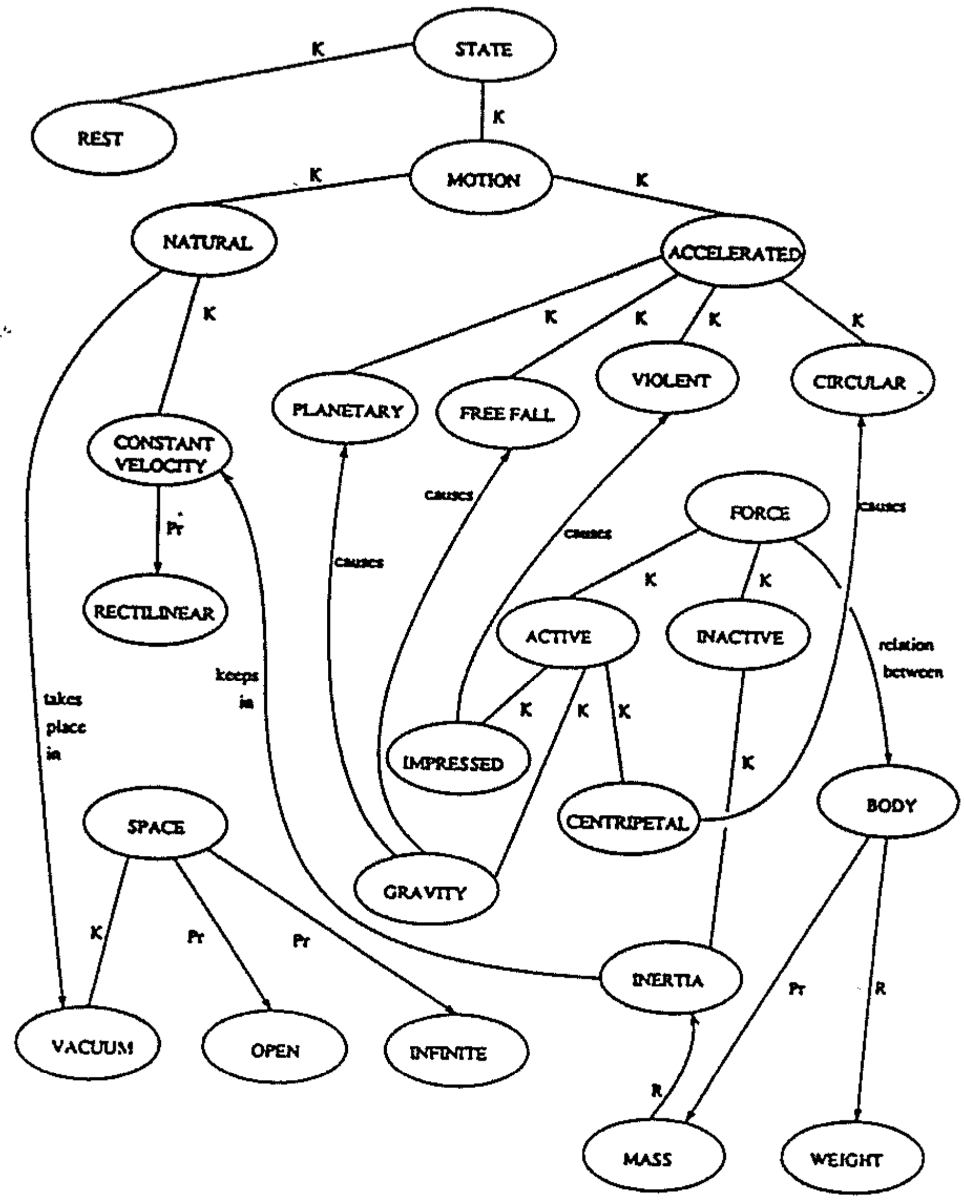


FIGURE 2: CONCEPTUAL NET (MEDIEVAL) (From N. Nersessian, 1989, p.171, "Conceptual change in science and science education", *Synthese, 80(1),* 163-184. Used with kind permission of the author and Springer Science and Business Media.)



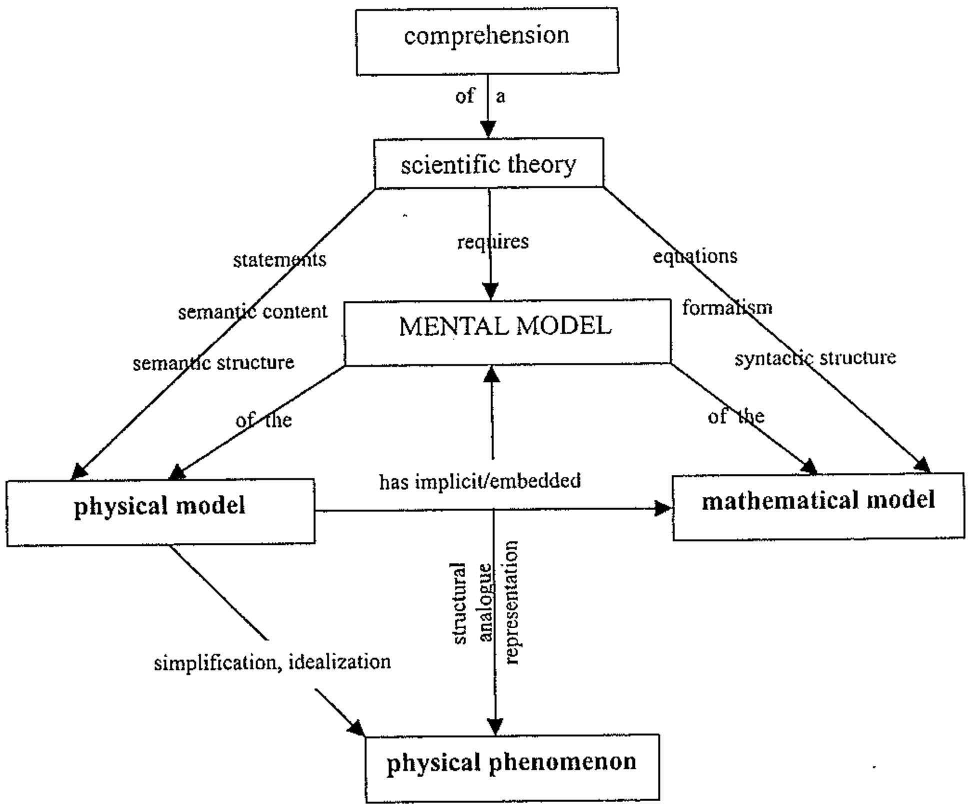
Partial conceptual structure of the medieval theory of motion.

FIGURE 3. NEWTONIAN CONCEPTUAL NET (From N. Nersessian, 1989, p.173, "Conceptual change in science and science education", *Synthese, 80(1),* 163-184. Used with kind permission of the author and Springer Science and Business Media.)



. Partial conceptual structure of the Newtonian theory of motion.

FIGURE 4: MODEL SCHEMATIC (From Greca and Moreira, 2001, p.111)



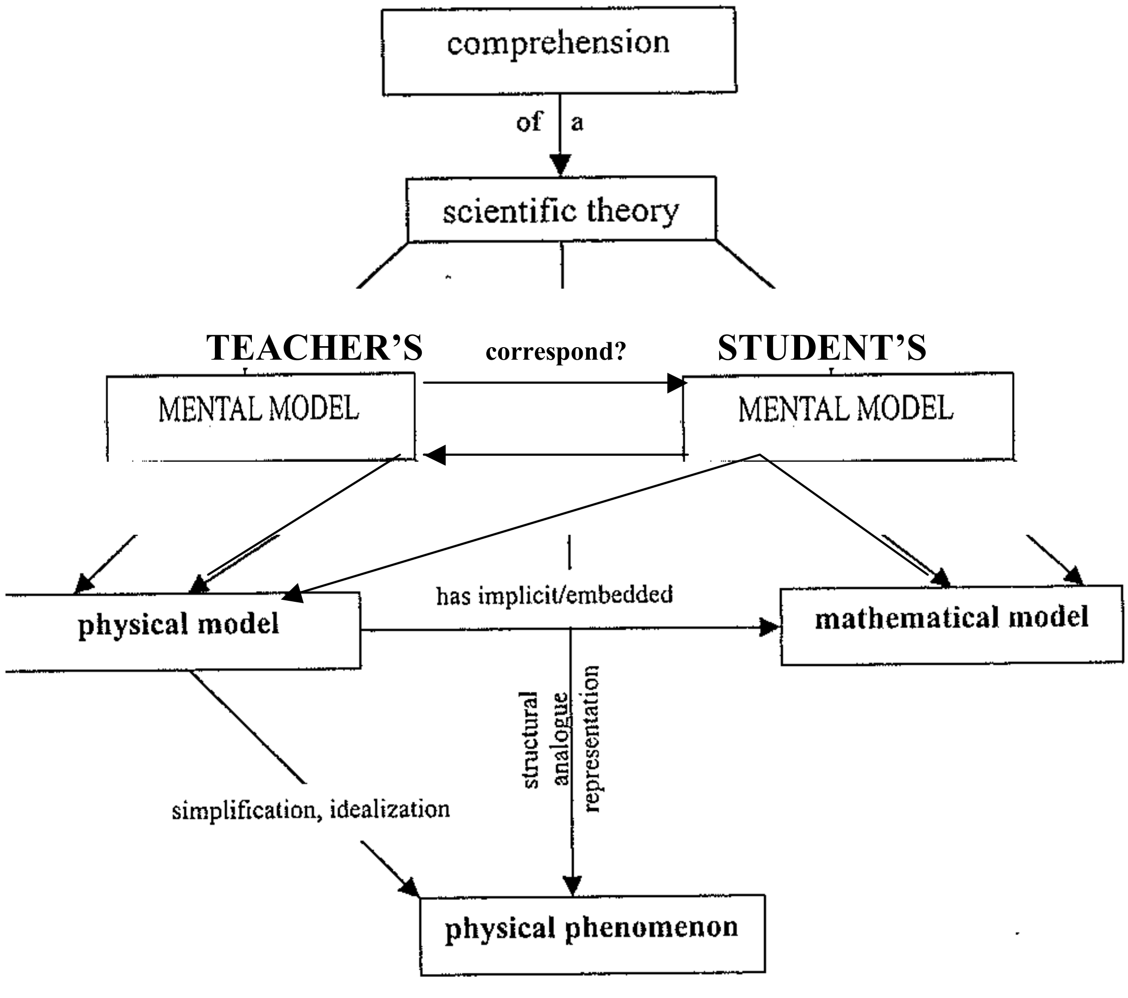


FIGURE 5. **DUAL SCHEMATIC** showing both a student's and teacher's corresponding mental models and relation to the scientific *theoretical* (physical and mathematical) model (Adapted from Greca and Moreira, 2001).

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