Broadening the Ontological Perspectives in Science Learning: Implications for Research and Practice in Science Teaching *

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Abstract. The argument presented in this paper is that efforts designed to engender systemic advancements in science education for fostering the scientific literacy of learners are directly related to the ontological perspectives held by members of the discipline. In elaborating this argument, illustrative disciplinary perspectives representing three complementary aspects of science education are addressed. These three perspectives represent the disciplinary knowledge and associated dynamics of: (a) science students, (b) science teachers, and (c) science education researchers. In addressing the ontological perspectives of each, the paper emphasizes how interdisciplinary perspectives can accelerate progress in science education.

1 The Function of Ontology in Science Education

The focus of this paper is ontological functions rather than general philosophical issues. This section emphasizes the interrelationship of ontology with knowledge representation as considered in computer-oriented cognitive science. An ontology is the product of the study of categories of things that exist or may exist within a domain [1]. More specifically, the categories of an ontology consist of the predicates, concepts, or relationships used to represent, provide focus on, and allow discussion of topics in the domain. An ontology and its categories impose an intellectual structure on what the substantive aspects of a domain are and how they are characterized.

The issue of ontology is highly relevant to science students, science teachers, and science education researchers. From the standpoint of science students, ontology reflects the core concepts and principles within science that constitute the major learning goal. To achieve the learning goal, students must understand how the hierarchical structure of a domain translates directly into building a schematic framework for core concepts and core concept relationships which serves as the basis for knowledge applications and as prior knowledge for further learning.

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The ontological framework for teachers and researchers in science education is broader than that of students because, in addition to core science content,their framework must include the additional pedagogical and/or research knowledge that represents their professional roles. For teachers, their expanded ontological function has to do with the conceptual understanding of both the science to be taught and the means for planning, conducting, and communicating all aspects of science teaching. For researchers, their expanded ontological function encompasses that of teachers along with the additional knowledge (e.g., theories, research findings, research methodology) that forms the intellectual basis for being a member of the science education research community.

An important issue relevant to this paper is the fundamental distinction between ontology and logic [1]. In comparison to an ontology which consists of a substantive categorization of a domain, logic is neutral. That is, logic itself imposes no constraints on subject matter or the way the domain may be characterized. As Sowa [1] noted, the combination of logic with an ontology provides a language that has the means to express extensible inferential relationships about the entities in a domain of interest.

2 Linkage Between Ontology and Knowledge Representation

Within cognitive science, the area of knowledge representation is closely related to that of ontology. As noted by Davis, Schrobe, and Szolovita [2], ontology determines the categories of things that exist or may exist and, in turn, these categories represent a form of ontological commitment as to what may be represented about a domain. At the same time, Sowa [1] pointed out that everyday knowledge is far too complex, fluid, and inconsistent to be represented comprehensively in any explicit system. Rather, because of the complexity of the world, knowledge is better considered a form of soup about which explicit systems of knowledge representation can only address selected structural aspects. Among the most important factors affecting consistency in the ontological representation of the same phenomena are multiple uses of the same words, vagueness in scientific language, and/or the interaction of multiple perspectives (i.e., different views).

As applied to science in general, every branch uses models that enhance certain features and ignore others, even within the hard (vs. behavioral) sciences. Areas of science can be considered as a collection of subfields, each focusing on a narrow range of phenomena for which the relevance of possible features is determined by a perspective for which details outside the primary focus of attention are ignored, simplified, or approximated. In the present paper, this suggests that the integration of interdisciplinary views, all relevant in different ways to the three aspects of science education (student learning, teaching, research), has a substantial potential to accelerate the advancement of disciplinary knowledge, even in the face of paradigmatic resistance from within the individual sub disciplines themselves (see [3]).

3 Knowledge-Based Instruction as a Framework for Science Education

An informal review of science education research trends in scholarly journals, handbooks, and textbooks revealed a surprising finding. In fact, relatively few of the studies in science education involve experimental (or field experimental) research that demonstrates the effect of approaches to or characteristics of science instruction on meaningful conceptual understanding by students in school settings [4]. Rather, the majority of science education studies (a) describe teacher experiences in science instructional settings, (b) evaluate student misconceptions (including reporting teacher frustration on the resistance of student misconceptions to conceptual change), or (c) use science content as an incidental research context (vs. focusing on in-depth science content) as a setting for the exploration of other concerns (e.g., equity/gender issues, use of professional development strategies, explorations focusing primarily on the processes of teaching using constructivist, cooperative learning, or inquiry/questioning strategies).

In comparison to science education, research from related disciplines (e.g., cognitive science, instructional psychology) provide rich perspectives and findings that bear upon the improvement of science teaching and learning. This section emphasizes research findings whose foundations which are grounded in interdisciplinary research fields having implications for improving student meaningful learning of science.

The idea of knowledge-based models comes from expert systems applications in computer science developed in late 1970. All such models met the requirement that the knowledge representing expertise was encoded in a fashion that was separate and distinct from other parts of the software that operated on the knowledge-base (e.g., to diagnose problems and offer advice). Building on the original expert systems, a new form of knowledge-based instructional architectures called intelligent tutoring systems (ITS) were developed in the 1980s [5]. In these systems, an explicit representation of knowledge to be learned provided an organizational framework for all elements of instruction, including the determination of learning sequences, the selection of teaching methods, the specific activities required of learners, and the evaluative assessment of student learning progress.

Figure 1 shows a propositional concept map that illustrates how concepts within a domain can be organized in a way to insure instructional coherence [6]. Using Figure 1 as a curricular framework, teachers are able to locate and then sequence reading/language arts and hands-on activities by linking them as elements to concepts on the map [7]. As a result, teachers are able insure that instruction is highly coherent in a manner that expands student in-depth science knowledge in a cumulative fashion. Referencing the curricular framework as a guide, teachers also are able to apply a coherent inquiry-oriented approach that (a) emphasizes what additional knowledge is learned over a sequence of related instructional activities that results in additional knowledge and understanding and (b) guides students to relate what they have learned as representations or elaborations of the core concepts. Overall, the foundational ideas underlying

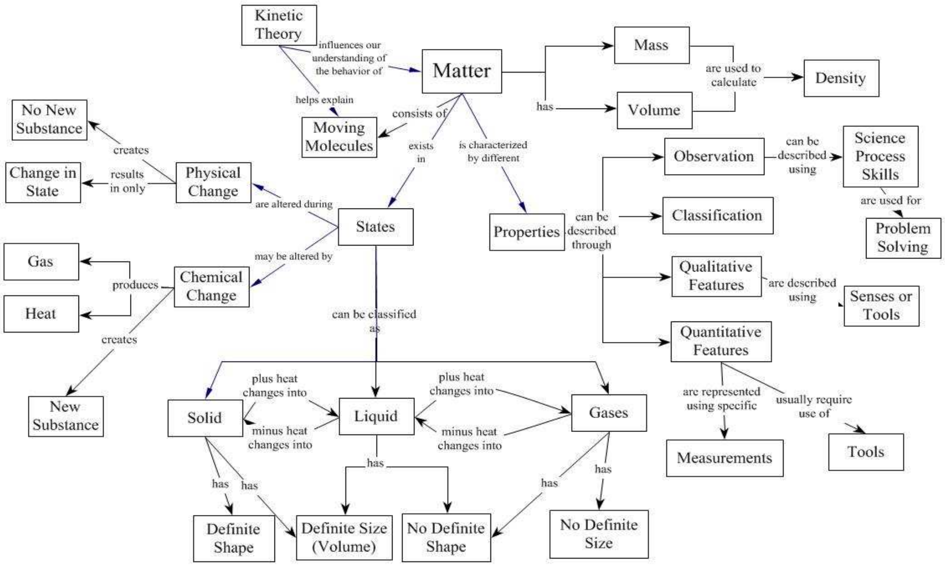

Fig. 1. Simplified illustration of a propositional curriculum concept map used by grade 3-4 Science IDEAS teachers to plan a sequences of science instructional activities[7].

knowledge-based instruction models are that (a) curricular mastery can be considered to be and approached as a form of expertise, and (b) the development of prior knowledge is the most critical determinant of success in meaningful learning.

The National Research Panel publication, How People Learn [8], serves as a guide for the interdisciplinary interpretation of the relevance of knowledge-based perspectives to science education. Focusing on meaningful learning, Bransford et al emphasized that to teach effectively, the knowledge being taught must be linked to the key organizing principles of that discipline. Such organized and accessible prior knowledge is the major determinant in developing the forms of cumulative learning consistent with the expertise characteristic of scientists. All forms of science pedagogy should explicitly focus upon the core concepts representing the ontological structure of the discipline.

In relating prior knowledge to meaningful learning, Bransford et al. [8] focused on the cognitive differences between experts and novices and showed that expert knowledge is organized in a conceptual fashion that differs from novices and that the use of knowledge by experts in application tasks is primarily a matter of accessing and applying prior knowledge under conditions of automaticity. Related is work by Anderson and others [9–11] who distinguished the strong problem solving process of experts as highly knowledge-based and automatic from the weak strategies that novices with minimal knowledge are forced to adopt in a trial-and-error fashion. Andersons cognitive theory suggests that all learning tasks should (a) consider all cognitive skills as forms of proficiency that are knowledge-based, (b) distinguish between declarative and procedural knowledge (i.e., knowing about vs. applying knowledge), and (c) identify the conditions in learning environments (e.g., extensive practice) that determine the transformation of declarative to procedural knowledge (i.e., apply knowledge in various ways).

In characterizing the learning processes, this interdisciplinary research perspective emphasizes that extensive amounts of varied experiences (i.e., initially massed followed by diverse distributed practice) involving the core concept relationships to be learned are critical to the development of expert mastery in any discipline [12]. Others [13] explored the conditions under which extensive practice to automaticity focusing on one subset of relationships results in the learning of additional subsets of relationships.

For science education, a knowledge-based approach suggests that the cumulative experiences of students in developing conceptual understanding (i.e., expertise) implies the development of a framework of general ontological (knowledge) categories in the form of core concepts/concept relationships. Thus, additional knowledge is first assimilated and then used as a form of expertise by students as prior knowledge for new learning. Such expertise facilitates students cumulatively acquiring, organizing, accessing, and thinking about new information that is embedded in comprehension and other meaningful tasks to which such new knowledge is relevant [14].

4 Ontological Implications of Knowledge-Based Instruction for Research and Practice in Science Education

Each of the perspectives illustrated below are grounded in disciplines other than science education. As a result, consideration of their potential application to science education has major ontological implications for the discipline and poses paradigmatic implications as well.

The major ontological implication for science learning is the importance of focusing all aspects of instruction on student mastery of core concepts and relationships. This implies a very different curricular approach at both the elementary and secondary levels (which typically emphasize a variety of rote hands-on activities), one that would emphasize the cumulative development of conceptual understanding that is consistent with that of scientists and has implications for significant curricular reform [7].

Within a knowledge-based context, the first consideration consists of a curricular distinction regarding the observational basis for science concepts taught [15]. They distinguished among three types of science concepts: (a) concepts which students could observe directly, (b) concepts which could be observed but for which observation was not feasible (e.g., observing the earth and moon from space), and (c) concepts which are artificial or technical symbolic constructs created by the discipline for which the notion of exhaustive direct observation within a learning setting does not apply (i.e., they represent labels for complex relationships that are tied to observation in an abstract fashion). Certainly the three types of concepts require substantially different curricular strategies for teaching [16] with types two and three being more difficult. However, in practice, virtually no distinction is made between them (e.g., young students are taught graphic representations of atoms and molecules with no operational association to observable phenomena), a curricular consideration that impacts teaching and learning in science.

Presented next are interdisciplinary research exemplars that have ontological implications for science education, considered from a knowledge-based approach to student learning. Each serves two major functions. The first is to illustrate one or more major points within applied science learning contexts or experimental settings. The second is to point out that despite the fact that the exemplars provide specific implications for improving the quality of school science instruction, they cannot be represented within the current ontological framework of science education at the appropriate level of detail.

The curricular findings of the highly-respected TIMSS study [17] provide a strong knowledge-based framework for considering the exemplars presented. In comparing the science curricula of high achieving and low achieving countries, the TIMSS study found that the curricula of high achieving countries were conceptually focused (on core concepts), coherent, and carefully articulated across grade levels while that in low-achieving countries emphasized superficial coverage of numerous topics with little conceptual emphasis or depth and that were addressed in a highly fragmented fashion.

The first exemplar is the work of Novak and Gowin[18] who studied the developmental understanding of science concepts by elementary students over a 12 year period. In their longitudinal study, concept maps were used to represent the cumulative development of student understanding of science topics based on interviews and initiated the use of concept maps by students to enhance their understanding of science [19]. Overall, these studies demonstrated the importance of insuring students have the means to understand the development of their own views of core concept relationships.

The second exemplar is a videodisk-based instructional program by Hofmeister et al. [20] that focuses on the development of core science concepts in physical science (e.g., heating, cooling, force, density, pressure) that are necessary to understand phenomena in earth science (e.g., understanding how the concept of convection causes crustal, oceanic, and atmospheric movement). Two complementary studies are relevant here. Muthukrishna [21] demonstrated experimentally that use of the videodisk-based materials to directly teach core concepts was an effective way to eliminate common misconceptions (e.g., cause of seasons) of elementary students while Vitale and Romance [22] showed in a controlled study that the use of the same instructional program resulted in mastery of the core concepts by elementary teachers (vs. control teachers who demonstrated virtually no conceptual understanding of the same content). These studies suggest that focusing instruction on core concepts is important for meaningful learning in science.

The third exemplar is a series of studies at the elementary and postsecondary levels. In an analyses of learning by elementary students, Vosniadou[23] showed that concepts have a relational nature that influences their order of acquisition in order for students to gain meaningful understanding. Dufresne et al. [24] found that postsecondary students who engaged in analyses of physics problems based upon a conceptual hierarchy of relevant principles and procedures were more effective in solving problems. Complementing these two studies, Chi et al. [25] showed that success in application of science concepts was facilitated by amplifying student understanding of the hierarchical organization of science concepts, findings aligned with TIMSS.

The fourth exemplar is a series of field-experimental studies with upper elementary students by Romance and Vitale[7] in which they implemented an integrated instructional model, Science IDEAS, that combined science concepts, hands-on activities, reading comprehension, and writing for 2 hours daily (as a replacement for reading instruction). Teachers used core science concepts as curricular guidelines (see Figure 1) for identifying and organizing all instructional activities while also emphasizing students learning more about what had been learned.

In applying an ontological perspective to the preceding issues, it is important to keep in mind that many interdisciplinary controversies reflect semantic rather than substantive concerns. However, overall, the issue of how to address science education ontologically is of paradigmatic importance in that an interdisciplinary approach would imply a substantial advancement in knowledge and understanding of the science teaching-learning process.

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