Interdisciplinary Perspectives for Broadening the Scientific Research Base in Science Education [1] [2]

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A major goal of science education research is the cumulative generation of pedagogical knowledge that can be used to improve meaningful understanding of science concepts by students. Using present initiatives in science education as a foundation, this paper overviews developments in cognitive science and instructional psychology along with associated exemplary research findings and implications that provide science education researchers with an interdisciplinary framework for improving the quality of school science teaching and learning.

An Interdisciplinary Framework for Overviewing Science Education Research

As a subject of formal study, the discipline of science consists of two complementary components (AAAS, 1993). The first is the conceptual and factual knowledge that pertains to understanding the different domains of science (e.g., understanding the operations of the physical world, the living environment, and the human organism). The second addresses the nature of scientific inquiry which represents the process through which the knowledge of science is established. The purpose of the field of science education is to apply the methods of scientific inquiry to advance pedagogical knowledge of how students are best able to gain a meaningful understanding of science content and the nature of science. In doing so, the field of science education applies the processes of science in order to teach science more effectively. The resulting pedagogical knowledge represents the content of the field of science education.

A primary issue of science education is to identify what students must do to demonstrate their in-depth understanding of science in a manner that parallels that of scientists. This issue is important because all science education research requires that student performance be measured and evaluated in some form. Although different approaches to classroom testing (e.g., multiple choice, performance, portfolio) are current topics in science education (see Mintzes et al, 2000), the methods of science themselves involving prediction, control, and interpretive explanations to phenomena that occur prescribe an overall framework for assessing student understanding (see Romance & Vitale, 1994).

Science and science education are complex and overlap, but certain characteristics clearly distinguish them. First, science can be considered broadly as a process for establishing knowledge that leads to prediction or control of events. Second, the processes of science can be considered to generate knowledge in the different domains of science (e.g., physics, earth science, biology). Third, student learning of both the resulting knowledge of science and the process of scientific inquiry are subjects of study in school settings. Fourth, science education, using the processes of science, focuses upon the development of pedagogical knowledge that improves science teaching.

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A Selective Overview of Science Education Research

General Status of Research in Science Education

An informal review of recent research by science educators in scholarly journals (e.g., *Journal of Research in Science Teaching)*, handbooks (e.g., Gabel, 1994; Fraser & Tobin, 1998a, 1998b), and representative textbooks revealed a surprising finding. Relatively few studies in science education involve experimental (or field experimental) research that demonstrates the effect of instructional characteristics on meaningful conceptual understanding by students in school settings. Rather, the majority of science education studies (a) describe teacher experiences in science instructional settings, (b) evaluate student misconceptions, or (c) use science content as an incidental research context for exploring other research concerns. In comparison, recent research from the related disciplines of cognitive science and instructional psychology provide a rich source of perspectives, findings, and implications. The remainder of this paper emphasizes research findings grounded in these related fields and their implications for improving student meaningful understanding of science.

Research-Based Interdisciplinary Principles Related to Science Education

A National Research Panel publication, *How People Learn*, edited by Bransford et al (2000) offers an important guide for future research in science education. Focusing on the question of meaningful learning, the publication stresses that to teach effectively in any discipline, the information taught must be linked to the key organizing principles (or core concepts) of that discipline. In this regard, well-organized and readily accessible prior student conceptual knowledge is the major determinant of the forms of cumulative meaningful student learning that are characteristic of scientists (see also Hirsch, 1996). From this cognitive science research perspective, all forms of science pedagogy must focus instructional (and assessment) activities upon the core concepts that reflect the underlying logic of the discipline.

A major research area relating to the role of prior knowledge in meaningful learning reviewed by Bransford et al (2000) focused on the cognitive differences between experts and novices. This research has shown that expert knowledge (i.e., expertise) is organized in a conceptual fashion that is very different from that of novices and that the use of knowledge by experts in application tasks (e.g., analyzing and solving problems) is primarily a matter of accessing and applying prior knowledge (e.g., Klodner, 1993, 1997) under conditions of automaticity. Related to this view is earlier work by Anderson and others (Anderson, 1992, 1993, 1996; Anderson & Fincham, 1994) 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. Also directly related to the preceding are key elements in Anderson’s cognitive theory that (a) consider all cognitive skills as forms of proficiency that are knowledge-based, (b) distinguish between declarative and procedural knowledge, and (c) identify the conditions that determine the transformation of declarative to procedural knowledge.

As characteristics of learning processes, this research emphasizes that extensive amounts of varied experiences (i.e., practice) involving the core concept relationships to be learned are critical to the development of expert mastery in any discipline. In complementary research, Sidman (1994) and others (Dougher & Markham, 1994; Artzen & Holth, 1997) have explored the conditions under which extensive practice to automaticity focusing on one subset of relationships can result in the learning of additional subsets of relationships that are not taught, but rather implied by the original subset of taught relationships (i.e., equivalence relationships). Niedelman (1992) and Anderson (1996) have offered interpretations of the research issues relating to how the amount and kinds of initial learning are related to transfer of initial learning to applied settings. A parallel area of such research has used knowledge-based architectures to develop computer-based intelligent tutoring systems (ITS) since the early 1980's (Kearsley, 1987).

Knowledge-based models broadly emphasize the development and organization of knowledge in a manner that is reflected in three forms of exemplary research: (a) the development of expertise summarized by Bransford et al (2000) and Anderson (e.g., Anderson, 1992, 1993, 1996; Anderson & Fincham, 1994), (b) the work of Kolodner and her colleagues (1993, 1997) on case-based knowledge representation and reasoning, and (c) the ontological development of knowledge categories offered by Sowa (2000). In the latter, an important perspective is that the cumulative experiences of students in developing in-depth conceptual understanding (i.e., expertise) results in the development of a framework of knowledge categories (see Dansereau, 1995; Medland & Vitale, in press) in the form of core concepts and relationships. Within such a framework, additional knowledge is first assimilated and then used by students as prior knowledge for new learning. In turn, this expertise facilitates students cumulatively acquiring, organizing, accessing, and thinking about new information that is embedded in both reading comprehension and meaningful learning tasks to which such knowledge is relevant (see Vitale et al, 2002).

Exemplars of Interdisciplinary-Oriented Science Education Research

TIMSS as a framework for research exemplars. The curricular findings of the highly-respected TIMSS study (Schmidt et al, 1999) provide a strong intellectual framework for the following research exemplars. TIMSS found that the curricula of high achieving countries was conceptually focused, coherent, and carefully articulated across grade levels. In contrast, the curricula in low-achieving countries (including the U.S.) emphasized superficial coverage of a wide range of topics with little conceptual emphasis or depth in a highly fragmented fashion.

Research exemplars in science education. The research studies reported here are intended to provide representative examples amplify implications of the research findings.

The first exemplar consists of work by Novak and Gowin (1984) who studied the developmental understanding of science concepts by elementary students. As their original work based on Ausubel's (1968) theory of cognitive learning evolved, they initiated the use of concept maps by students to enhance their meaningful understanding of science. Related work has been reported by Fisher et al (2000) and Mintzes et al (1998). Overall, these studies demonstrated the importance of students having the means to perceive and reflect on the development of their views of core concept relationships.

The second exemplar is a videodisk-based instructional program by Hofmeister et al (1989) that focuses on the development of core concepts in physical science (e.g., heating, cooling, force, density, pressure) to understand phenomena in earth science. Two complementary research studies are relevant. Muthukrishna et al (1993) demonstrated that using the videodisk instruction to teach core concepts directly was effective in eliminating student misconceptions. Vitale and Romance (1992) showed that the videodisk program resulted in mastery of the same core concepts by elementary teachers (vs. control teachers who displayed no conceptual understanding of the same content). In much the same way as TIMSS (see Novak & Gowin, 1984), these studies suggest that focusing instruction on core concepts is important for meaningful learning by students and teachers alike.

The third exemplar is a series of studies at the elementary and postsecondary levels. Vosniadou (1996) showed the importance of focusing instruction on the relational nature of science concepts in order for students to gain meaningful understanding. Dufresne et al (1992) found that postsecondary students using a conceptual hierarchy of relevant principles and procedures in the analyses of physics problems were more effective in solving problems. Leonard et al (1994), Chi et al (1981), and Heller and Reif (1984) showed that success in application of science concepts was facilitated by amplifying student understanding of the hierarchical organization of science concepts. The findings of these experimental studies parallel the descriptive findings of TIMSS.

The fourth exemplar is a series of field-experimental studies with upper elementary students by Romance and Vitale (2001) that encompass many of the preceding research principles. Their integrated knowledge-based instructional model, Science IDEAS, combines in-depth science instruction involving reading science materials and writing about science within daily 2-hour time blocks that replace regular reading and language arts instruction. Implemented within a broad inquiry-oriented framework, teachers use core science concepts as curricular guidelines for identifying, organizing and sequencing the different instructional activities in which students engage. Results of a series of studies (Romance & Vitale, 2001) showed that students participating in Science IDEAS instruction obtained significantly higher levels of achievement in both science and reading comprehension as measured by nationally normed standardized tests. In addition, the knowledge-based elements of Science IDEAS were successfully extended to postsecondary science instruction in chemistry and biology (see Haky et al, 2001; Romance et al, 2002). This extension emphasized (a) the use of core concepts and concept relationships as a curricular framework for teaching and (b) student use of propositional concept mapping to enhance reading comprehension of science texts and to guide review and study. Overall, this series of studies is supportive of a knowledge-based approach to science instruction.

Conclusions and Implications

From a knowledge-based perspective, the overall principles for sound science are: (a) all aspects of science instruction must focus on core science concepts, (b) curricular mastery by students can be considered to be and approached as a form of expertise characteristic of experts, and (c) the development of conceptual prior knowledge is the most critical determinant of success in future meaningful learning. In this regard, there is a critical need for research in school settings focusing on the cumulative effects of in-depth understanding of core concepts reflecting the logical structure of the discipline. In addition, within such a research context, combining the representative interdisciplinary research in this paper with those in science education has the potential to magnify the advancement of scientific knowledge in all of these related fields.

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