CHAPTER 21

Research in Science Education: An Interdisciplinary Perspective[1]

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The continuing goal of science education research is the 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, we provide an overview of developments in cognitive science and instructional psychology and associated exemplary research findings and implications that provide researchers and practitioners with an interdisciplinary framework for improving the quality of school science instruction.

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—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 cumulative knowledge of science is established—understanding the process of scientific research. Even though the teaching and learning of science within elementary, secondary, and postsecondary educational settings differ substantially in sophistication, all three are linked pedagogically by these two common components of science content and process. In turn, at any level of sophistication, these two components are fundamental to the concept of scientific literacy.

The purpose of the field of science education is applying the methods of scientific inquiry to advance pedagogical knowledge of how students are gain a meaningful understanding of science content and the nature of science. In other words, the goal of the field of science education is to use the processes of science to establish knowledge that, when applied, results in science being taught more effectively. The resulting pedagogical knowledge represents the content of the field of science education—how to teach, for example, physics, Earth science, or biological principles more effectively.

Within science education, a primary methodological issue is identifying what students must do to demonstrate an in-depth understanding of science. This issue is important because all science education research requires that student performance be observed, measured, and evaluated in some form. Although different approaches to classroom assessment—such as multiple choice, performance, portfolios—are topics current in science education (Pellegrino et al. 2001), the methods of science themselves prescribe an overall framework for assessing student understanding (Metzenberg et al. 2004; Mintzes et al. 1999; Ruiz-Primo et al. 2002). Specifically, students demonstrate understanding of scientific concepts and principles in the same manner as scientists (Vitale and Romance, forthcoming)

- by linking knowledge to observable phenomena,
- by applying their knowledge to make specific predictions of future events—such as predicting that when a substance is heated, the substances will expand—and/or to manipulate conditions to make future events occur—such as making a substance expand by heating the substance, and
- by organizing their knowledge in terms of core concepts and concept relationships as a form of expertise (Bransford et al. 1999).

In a complementary fashion, students who have such forms of understanding also can

- apply science knowledge abductively by suggesting plausible reasons why phenomena may have occurred—such as if something expanded, a possible reason is that it was heated).

Although not always addressed explicitly in science education, the preceding suggests how meaningful understanding of discipline-specific science concepts (and principles) provides students at all levels with a substantive framework for applying both scientific knowledge—why expansion joints are used in bridges—and the processes of science —scientifically testing the plausibility of whether a substance expanded because it was heated.

Although science and science education are complex and overlap, certain characteristics clearly distinguish them.

- First, *science* can be considered broadly as a process for establishing and organizing cumulative knowledge that leads to prediction or control of events.
- Second, the *processes of science* can be considered as the means for generating such 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 in school settings is the domain of *science education*, and,
- Fourth, the domain of *science education research*, using the processes of science, focuses upon the development of pedagogical knowledge that improves teaching of science content and process.

Research Overview: An Interdisciplinary Perspective

This section consists of three parts whose combined understanding serves as an interdisciplinary-oriented guide for science educators and science education researchers.

The first part of this section informally summarizes and interprets the status of research activity in science education.

The second part overviews recently emerging principles in cognitive science and related disciplines that offer a strong research-based foundation for the future advancement of science education.

The third part presents examples of research in science education that embody these principles and provide concrete models for researchers and practitioners.

Building upon the three parts in this section, the following sections provide an overview of the implications of interdisciplinary research perspectives along with recommendations for science education research and practice.

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Status of Research in Science Education: An Informal Appraisal

An informal review of recent research by science educators in scholarly journals—such as *International Journal of Science Education, Journal of Research in Science Teaching,* and *Science Education*; handbooks (Fraser and Tobin 1998a, 1998b; Gabel 1994); and textbooks revealed a surprising finding. Relatively few 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. Rather, the majority of science education studies (a) describe teacher experiences in science instructional settings, (b) evaluate student misconceptions—including reporting teachers' frustration on the resistance of student misconceptions to conceptual change, or (c) use science content as an incidental research context for investigating other issues such as equity/gender issues, professional development strategies, and focusing on the processes of teaching, versus achievement outcomes, using constructivist, cooperative learning, or inquiry/questioning strategies.

In comparison to research on science education, recent research from related disciplines such as cognitive science (Bransford et al. 1999), educational psychology (Mayer 2004), and instructional psychology (Grossen et al. 2001) offers a rich source of interdisciplinary perspectives and findings (see Romance and Vitale 2002). The field of science education is largely unaware of this research, despite its potential for systemically improving the understanding of how students gain in-depth science knowledge from school instruction. The remainder of this section presents principles and exemplary interdisciplinary research findings whose foundations are grounded in these related fields and that offer implications for systemically improving student science learning.

Research-Based Principles for Science Education

A recent publication by the National Research Panel, *How People Learn* (Bransford et al. 1999) serves as an important guide for research in science education. Focusing on meaningful student learning, the publication stresses that to teach effectively in any discipline, the information being taught must be linked to the key organizing principles, or core concepts, of that discipline. Well-organized and readily accessible prior student conceptual knowledge is the major determinant of the forms of cumulative meaningful student learning characteristic of scientists, a principle also expressed by Hirsch (1996). From this research perspective, all forms of science pedagogy should focus instructional, and assessment, activities on the core concepts that reflect the underlying logic of the discipline.

Prior knowledge and meaningful learning: Expert versus novice research. A major area of research relating to the role of prior knowledge in meaningful learning that Bransford et al. reviewed focused on the cognitive differences between experts and novices. This research has shown repeatedly that expert knowledge is organized in a conceptual fashion very different from that of novices' knowledge and that the use of knowledge by experts in application tasks such as analyzing and solving problems is primarily a matter of accessing and applying prior knowledge (Kolodner 1993, 1997) under conditions of automaticity. Related to this view is earlier work by Anderson and others (Anderson 1992, 1993, 1996), who distinguished the "strong" problem-solving process of experts that is highly knowledge-based and automatic from the "weak" strategies that novices with minimal knowledge must adopt in a trial-and-error fashion. Directly related 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 (i.e., knowing about versus applying knowledge), and (c) identify the conditions in learning environments—extensive practice—that determine the transformation of declarative to procedural knowledge, learning to apply knowledge in various ways.

This research emphasizes that extensive amounts of varied experiences—practice—involving the core concept relationships to be learned are critical to the development of expert mastery in any discipline. In related research, Sidman (1994) and others (Dougher and Markham 1994; Artzen and Holth 1997) have explored the conditions under which extensive practice to the stage of automaticity focusing on one subset of relationships can result in the learning of additional subsets of relationships. In their work, these additional relationships were not taught but rather were implied by the original subset of relationships that were taught (i.e., equivalence relationships). In other relevant work, Niedelman (1992), Anderson (1996), and Goldstone and Son (2005) have offered interpretations of the research issues relating to how the amount and kinds of initial learning—such as degree of original mastery and interaction of concrete experiences in varied contexts and abstract perspectives—are related to transfer of initial learning to applied settings.

Explicit knowledge representation: Research on intelligent tutoring systems. A parallel area of research addresses the knowledge-based architecture of computer-based intelligent tutoring systems (ITS) developed in the early 1980s (Kearsley 1987; Luger and Stubblefield 1998). In these systems, an explicit representation of the knowledge to be learned provides 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 success. Specifically, from the standpoint of assessment, knowledge-based instructional models provide a sequence of interrelated activities that provided teachers with an authentic context for evaluating cumulative student meaningful understanding.

Knowledge-based instruction versus metacognitive strategies. Although there is a well-established research literature (Bransford et al. 1999) that focuses on the importance of "content-free" metacognitive strategies—such as use of general strategies by students to facilitate their learning, a knowledge-based approach primarily emphasizes the development and organization of prior knowledge in a manner that is reflected in three research areas: (a) the development of expertise summarized by Bransford et al. (1999) and Anderson (1992, 1993, 1996); (b) the work on case-based knowledge representation and reasoning—remembering and applying past problem-solving scenarios provides a powerful context for approaching the next problem—developed by Kolodner and her colleagues (1997); and (c) the general development of knowledge categories offered by Sowa (2000).

From a knowledge-based approach, research on the use of general metacognitive strategies has greater potential relevance for novices than for experts who have an in-depth understanding of science conceptual content (see Anderson 1987). Because such general metacognitive research is contextualized within a framework of science learning by novices, it has minimal relevance to enhancing the forms of meaningful in-depth science understanding that are characteristic of experts. Rather, a more promising view of meaningful science learning as knowledge-based has a greater potential value for researchers and practitioners. Specifically, a knowledge-based perspective holds that the cumulative experiences of students in developing in-depth conceptual understanding (i.e., expertise) results in the development of a framework of general knowledge categories (Dansereau 1995; Vitale and Medland 2004) in the form of core concepts and concept relationships. Within such a framework, additional knowledge is first assimilated and then used by students as prior knowledge for new learning as a form of expertise (see Mayer 2004). In turn, this expertise facilitates students' cumulatively acquiring, organizing, accessing, and thinking about new information that is embedded in reading comprehension and meaningful learning tasks to which the new knowledge is relevant (Vitale et al. 2002).

Implications for science education research from cognitive science. From a knowledge-based perspective, the overall principles of relevance to both researchers and practitioners for sound science instruction are as follows:

- All aspects of science instruction should focus on the development and organization of core science concepts;
- Both the curricular structure of instruction and curricular mastery by students should be considered to be and approached as a form of expertise (i.e., representing the form of science understanding characteristic of experts); and
- The development of conceptual prior knowledge is the most critical determinant of future success in meaningful learning.

In this regard, the study of how cumulatively focusing on the core concepts and relationships that reflect the logical structure of the discipline and enhancing the development of prior knowledge are of paramount importance for meaningful learning to occur is an expanding research trend. Additionally, the preceding, as potential standards for sound science instruction that focuses on both science content and science processes are consistent with the results of the Third International Math and Science Study (TIMSS) presented as a framework for the following section (Schmidt et al. 1999, 2001).

Exemplars of Science Education Research

This section presents five research exemplars that serve two major functions. The first is that they illustrate one or more major points presented above within a research context that is directly relevant to applied science learning settings. The second is that, considered together, they provide systemic implications for improving the quality of science instruction in schools, and therefore for broadening the foundation of science education research. The exemplars are presented using the major curricular findings of the TIMSS study (Schmidt et al. 1999, 2001) as an overall conceptual framework in a fashion that complements the parallel ideas presented in the Bransford et al. (1999) report.

The TIMSS study as a framework for research exemplars. The curricular findings of the highly-respected TIMSS study (Schmidt et al. 1999, 2001) provide a strong intellectual framework for the research exemplars presented. In comparing the science and mathematics curricula of high-achieving and low-achieving countries, the TIMSS study reported a major conclusion that is consistent with the research above. Specifically, the TIMSS study found that the curricula of high-achieving countries was characterized as focused around big ideas, conceptually coherent, and carefully articulated across grade levels. In contrast, the curricula in low-achieving countries (including the U.S.) emphasized superficial, highly-fragmented coverage of a wide range of topics with little conceptual emphasis or depth (i.e., U.S. curriculum was "a mile wide and an inch deep"). In general, the findings of the TIMSS study and the supporting perspectives from Bransford et al. (1999) offer a useful framework for the exemplars that follow. The small number of research studies reported here are intended to provide researchers and practitioners with examples that facilitate understanding of the implications of the research.

Using concept mapping as a knowledge-elaboration tool. The first exemplar consists of work by Novak and Gowin (1984) who studied the developmental understanding of science concepts by elementary students over a 12-year period. Their work, which was based on Ausubel's theory of cognitive learning (1968), is highly consistent with contemporary cognitive science research principles. In a longitudinal study, they used concept maps to represent the cumulative development of student understanding of science topics based on interviews. As their original work evolved, these two researchers initiated the use of concept maps by students to enhance meaningful understanding of science. Related work has been reported by Fisher et al. (2000), Mintzes et al. (1998), and Romance et al. (2000). These studies have demonstrated the importance of students' having the means to perceive and reflect on the development of their own views of core concept relationships.

Focusing instruction directly on core concepts. The second exemplar is a videodisc-based instructional program by Hofmeister et al. (1989) that focuses on the development of core science concepts in physical science (e.g., heating, cooling, force, density, and pressure) to understand phenomena in Earth science (e.g., understanding how the concept of convection causes crustal, oceanic, and atmospheric movement). Two representative studies are relevant here. Muthukrishna et al. (1993) demonstrated experimentally that instructional use of the videodisc-based materials to directly teach core-concepts was an effective way to eliminate common misconceptions (e.g., seasons and day and night) of elementary students in science. Vitale and Romance (1992) showed in a controlled study that the use of the same core-concept-focused instructional program resulted in mastery of the same core concepts by elementary teachers (versus control teachers who demonstrated virtually no conceptual understanding of the same content). In much the same way as did TIMSS (Schmidt et al., 1999, 2001) and Novak and Gowin (1984), these studies suggest that focusing instruction on core concepts, including principles, is an important element in developing meaningful student learning.

Using direct instruction to enhance student learning. The third exemplar is an experimental study by Klahr and Nigam (2004) that found teacher-guided direct instruction far more effective than a discovery approach not only on student initial acquisition of a procedure for designing and interpreting simple unconfounded experiments, but also on subsequent application/transfer. In interpreting their findings, the perspectives offered by Klahr and Nigam were consistent with a more general analysis of the potential role of direct/guided instruction in meaningful science learning presented by Mayer (2004). In turn, both perspectives are consistent with more general approaches in instructional science (e.g., Engelmann and Carnine 1982; Grossen et al. 2001) that address technical issues in the design of optimally effective learning environments.

Using the conceptual structure of the discipline as a basis for problem solving. The fourth exemplar is a series of studies at the elementary and postsecondary levels. In an analysis of learning by elementary students and of associated instructional materials, Vosniadou (1996) emphasized 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 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, carefully designed experiments by 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 the TIMSS study and ideas presented by Bransford et al. (1999).

Using meaningful learning in science as a basis for improving reading comprehension. The fifth exemplar is a series of experimental studies with upper elementary students by Romance and Vitale (2001) that encompass many of the preceding research principles. Their integrated instructional model, Science IDEAS, combined science, reading comprehension, and writing within a daily two-hour block that replaced regular reading and language arts instruction. During that time students engaged in science learning activities that involved hands-on science experiments and projects; reading science texts, trade books, and internet-accessed science materials; writing about science; journaling; and using concept mapping as a knowledge representation tool. As an intervention implemented within a broad inquiry-oriented framework, teachers used core science concepts as curricular guidelines for identifying, organizing, and sequencing the different instructional activities in which students engaged. Both within and across lessons, all aspects of teaching emphasized students' learning more about what had been learned previously in order to engender cumulative student in-depth science understanding.

A series of studies exploring the effectiveness of the model (Romance and 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 such as the Metropolitan Achievement Test—Science and the Iowa Tests of Basic Skills—Reading Comprehension. In addition, compared to controls, Science IDEAS students displayed significantly more positive attitudes toward science learning both in and out of school, greater self-confidence in learning science, and more positive attitudes toward reading in school. In addition, in follow-up studies, the researchers extended elements of the Science IDEAS intervention to postsecondary science instruction in chemistry and biology (Haky et al. 2001; Romance, Haky, et al. 2002). These extensions 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. Considered together, this combined series of studies supports the effectiveness of a knowledge-based approach to science instruction.

Integration of major points of the science education research exemplars. The following summarizes the major points of the research exemplars from two perspectives:

- As instructional guidelines for practitioners, and
- As a set of contextual characteristics that are required for the ecological validity of research investigating science instruction as a cumulative learning process.

Specifically, these points are:

- A comprehensive science curriculum should include the study of both science knowledge and the nature of science (not just one of the two) as a requirement for science literacy,
- The curriculum focus of science instruction at all levels should be on the core concepts and concept relationships (i.e., principles) within the areas of science to be taught and learned (consistent with the conceptual organization of experts and representing the logic of the discipline),
- The overall framework of core concepts and core concept relationships should be articulated across grade levels in a clear and coherent fashion,
- All student learning activities, assessment practices, and teaching strategies should be directly related to the overall core concept framework,
- Students should experience a variety of learning activities for developing meaningful science understanding of core concepts, including the use of concept mapping as a knowledge representation tool,
- Students should engage in a variety of application and problem-solving experiences after the initial development of meaningful science understanding of the relevant science content, and

- Cumulative development of science understanding as students progress through school should be accomplished through the elaboration and detailing of core ideas previously introduced as much as is possible.

Implications of an Interdisciplinary Research Perspective for Improving Science Instruction

In this section, the implications of interdisciplinary research are considered from three perspectives: (a) directions for research in science education, (b) transformation of research into practice, and (c) building standards for research utilization by practitioners.

Implications for Science Education Research

Perhaps the most important implication of the preceding is that science education researchers should strive toward forming interdisciplinary perspectives that result in integrating their research with that of related disciplines. In doing so, researchers should recognize that such an initiative is consistent with both a constructivist view of knowledge development and the cumulative inquiry processes on which all science is based. Further, the integration of diverse disciplines should be recognized as a means for pursuing systemic disciplinary advancements (e.g., see Kuhn 1996; Hirsch 1996; Mayer 2004).

To advance understanding of science learning, science education researchers should consider the benefits of incorporating three emerging interdisciplinary areas of investigation into science education research. The first of these research areas is Engelmann and Carnine's (1982) Direct Instruction (DI) Model from instructional psychology. The DI Model attempts to provide an algorithmic framework that includes strategies for effectively teaching concepts, concept relationships, intellectual skills (as procedures), and cognitive routines that apply complex knowledge and skills. Additionally, the model includes strategies for the developmental articulation of curriculum-emphasizing core concepts that optimize retention, application, and use of knowledge and skills learned as facilitative knowledge for new learning. All of the algorithmic components of the DI Model could be applied and investigated in science learning frameworks. Of particular promise is using elements of the model to preteach core science concepts. These concepts would then serve as prior knowledge for students participating in the more informal, open-ended, and problem-based settings that are using the small-group inquiry formats that are favored by constructivist-oriented science educators (see Mayer 2004). Because the fields of DI and science education have different emphases, the present ontological framework of science education cannot represent the operational dynamics of the DI Model at the level of detail required for research without substantial interdisciplinary integration.

The second research area is Anderson's cognitive-science-based Adaptive Control of Thought (ACT) Model. Anderson's research (1992, 1993, 1996) provides a theoretical framework that focuses on the transition from novice to expert in terms of the interplay between the dynamics of the learning environment on one hand and the forms of declarative and procedural knowledge on the other. In one fashion or another, these are among the critical issues associated with the use of formal science instruction to build conceptual understanding from a knowledge-based and meaningful learning perspective.

Although complex, Anderson's and related work have yielded many important research findings (Blessing and Anderson 1996; Anderson and Fincham 1994, 1996; Anderson et al. 1997; Anderson and Sheu 1995; Wisniewski 1995). Included are techniques for the differential representation of declarative and procedural knowledge, processes for the development and refinement of cognitive skills, models addressing the transformation of declarative to procedural knowledge, models distinguishing between expert and novice problem solving, and models explaining the reorganization of skill patterns and knowledge structure in the development of expertise.

Anderson, with others, also has used his work as a foundation for critiquing research and policy issues in education (Anderson, Corbett et al. 1995; Anderson, Reder et al. 1995, 1996). Again, the point is that adapting Anderson's ACT model to research in science teaching—both of which depend on the observed structure of the environment in combination with prior knowledge as the basis for learning—could well advance the goals of science education. As with the DI model, the present ontological framework of science education cannot represent Anderson's ACT model at the level of detail required for research without substantial interdisciplinary integration.

As with DI, Anderson's ACT Model could be readily investigated, or applied, within science instruction scenarios. Of particular interest to science educators would be studies conducted with meaningful science content that addresses such issues as knowledge acquisition, automaticity, and the development of expertise, all in a fashion that would investigate characteristics of the instructional environment which, in terms of variables in the ACT model, engender such outcomes.

The third area is the area of equivalence relations in learning, or stimulus equivalence, conducted in behavior analysis research. Although highly experimental at present, this research (Sidman 1994) addresses how to engender learning outcomes that arise indirectly from instruction because they are based upon the structural properties (i.e., element relationships) of the knowledge to be learned. Because science is a structured content domain that is meaningful, it is an area that could benefit greatly from increased understanding of the equivalence relations phenomenon.

This research area addresses a general question of the development of generative inferential processes in learning (Baer 1997; Dougher and Markham 1994; Sidman 1994). More specifically, stimulus equivalence research focuses on understanding how the structure of knowledge and the conditions under which the parts of a structure that are taught can be made to result in learning outcomes that—in relation to the original knowledge structure—are far broader than what was taught explicitly (Artzen and Holth 1997; Eilseth and Baer 1997; Lane and Critchfield 1996; Lynch and Cuvo 1995).

These and other examples from the area of equivalence relations have significant implications for the development of curriculum design strategies that maximize student learning outcomes resulting from formal instruction in terms of learned-but-not-taught relationship-based content. In addition, the implications from this research area complement instructional design models, such as DI and Anderson's ACT model, that emphasize the direct teaching of conceptual relationships and strategies to pursue the development of prescriptive guidelines for accomplishing learned-but-not-taught outcomes through K–12 science instruction. Again, as with the DI and ACT models, the present ontological framework of science education cannot represent behavior analysis equivalence relations at the level of detail required for research without substantial interdisciplinary integration.

Perspectives for Transforming Research Into Practice

A second important interdisciplinary perspective for science education research is the transformation of research into practice. As represented in the specifications for federally funded proposals, such as those from the U.S. Department of Education Institute of the Education Sciences, the development of research knowledge can be approached as a multiphase process that (1) involves initial proof-of-concept demonstrations that (2) then evolve into controlled replicable research studies that, in turn, (3) evolve into scale-up initiatives within applied settings (see Coburn 2003; Vitale and Romance 2004) and, that, in the present context, (4) emphasize development of the capacity of school systems to sustain an application.

Although such a broad perspective may be of limited interest to many science education researchers, it is of primary importance to the discipline because of its implications for curricular policy. For example, Jones et al. (1999) found that school reform initiatives resulted in instructional time for science being reallocated to reading and language arts, raising a significant policy issue for science education. On the other hand, Romance et al. (forthcoming) reported research findings that replacing reading/language arts with science increased achievement in reading comprehension and language arts, while Guthrie et al. (2004) have consistently found that enhancing traditional elementary-level literature-oriented reading programs with science reading content enhanced reading achievement. The point is that while such research findings (see also, Duke et al. 2003; Walsh 2003) have implications for curriculum policy (see Romance et al. 2002), systemic changes in curricular practices require researchers themselves to address the question of the scale-up of their work to applied settings, an issue that is an active area of research and development (Coburn 2003; Vitale and Romance 2004).

Building Standards for Research

The effective use of and advocacy for research in science education must come from practitioners as societal representatives (Johnson and Pennypacker 1992). Although the U.S.-mandated No Child Left Behind initiative will include science, schools tend to meet accountability requirements by emphasizing short-term, within-grade test preparation rather than systemic change. As a result, the practice of "evidence-based" decision making by schools is far from optimal. In this regard, Hirsch (1996), Carnine (1995), and Mayer (2004) have offered a number of perspectives to which researchers should be sensitive. Primarily, science education researchers should first be advocates for the use of empirical research findings as a basis for school decision-making and, second, relate any form of advocacy of their or others' research findings to that general principle. By doing so, researchers are able to contribute toward the acceptance of a general evidence-based criterion of effectiveness that potential instructional initiatives must display prior to large-scale adoption in reform (see Carnine 1995).

Interdisciplinary-Based Recommendations for Research

We offer the following recommendations as a foundation for advancing the scope of future science education research by broadening its interdisciplinary foundations. Specifically, in planning their studies, science education researchers should consider recognizing and addressing issues relating to

- the ontological implications of interdisciplinary research perspectives,
- the ecological validity of findings by conducting research within environments that provide a valid curricular and assessment context for the cumulative in-depth learning of science,
- distinguishing among categories of science concepts (directly observable, real but not observable, constructed but not real) to be learned within different developmentally appropriate instructional contexts (see Romance and Vitale 1998),
- adapting a knowledge-based perspective for conceptual understanding as expertise and the role of such knowledge in understanding the nature of science and the use of metacognitive strategies,
- the importance of focusing research on identification and refinement of conditions that result in improved student understanding of science (as the goal of science education research), and
- the broadening of programmatic research design to encompass an evolution from proof-of-concept to controlled experimentation to demonstrated replicability in applied settings (i.e., scale up).

A Methodological Addendum [2]

Although this chapter's focus and research recommendations are substantive rather than methodological, it would not be complete without briefly recognizing three perspectives that together provide an important methodological foundation for modern science education research.

The first perspective has to do with the present advocacy for the importance of using completely randomized designs (CRDs) as a standard for experimentation whenever possible. Although included as a topic in most introductory textbooks, perhaps the most precise and clearest explanation of the rationale for using CRDs can be found in Raudenbush (2001). On a more general level, it should be recognized that the present emphasis on CRDs in the literature has a decidedly "per-separate-experiment" focus, despite the fact that the replicability of experimental findings across the widest possible range of settings is the key requirement for the acceptance of scientific knowledge. In this regard, researchers should consider a classic work by Sidman (1960) that presents methodological strategies that address the role of randomization within the broader research context of establishing the generalizability of research findings.

The second perspective, related to the first, has to do with estimating and reporting "effect size" as necessary methodological enhancements to the reported results of statistical tests of significance. A methodological overview of such approaches can be found in the recent *Publication Manual of the American Psychological Association* (2001) and is an active topic in the literature (also see Wilkinson 1999).

The third perspective is related to both of the preceding and addresses strategies for cumulative research design in applied settings as outlined by Slavin (1990, 2002). In these papers, Slavin distinguished between model-oriented and variable-oriented research by pointing to the fact that despite all systemic instructional interventions in applied settings being highly complex, such multifaceted models are the form of applications that practitioners must implement to enhance instructional quality through research. Within this context, he suggested a sequential design process in which applications of such models with fidelity (as a complex variable) are first validated as effective within experimental (CRD) studies. Then, after validation, the dynamics of the model are explored systematically.

Although beyond the scope of this chapter, the three perspectives represent methodological standards essential to incorporate in the pursuit of any of the recommendations for interdisciplinary research in science education developed in this chapter.

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[1] This research was supported by Grant No. 0228353 from the National Science Foundation Interagency Research Initiative and by Grant No. R305G04089 from the USDOE-Institute of the Education Sciences.

[2] The authors are indebted to an anonymous reviewer's suggestion that chapter would be of greater value if a brief note on methodological standards of practice was added.

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2006

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