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Introduction: Viewing the Domain of Science Education[1]

OUTLINE

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ABSTRACT

We find ourselves at a critical and exciting time in science education. It is critical because scholars from distinct disciplines are working on similar types of problems that have relevance for science education research and practice. Separate disciplines that explore a common ground of inquiry, that seek solutions to the same problem, that ask related questions, that draw from a related literature, and that share

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knowledge claims are referred to as "domains." Since the 1950s, advances in philosophy of science, cognitive psychology, and science education have led to the development of an "emerging domain" that seeks to understand the dynamics of the growth of scientific knowledge. The first part of this chapter describes how important ideas drawn from the different disciplines of the emerging domain have contributed to our knowledge of curriculum development and implementation of science curriculum. The second part presents an overview of the following chapters and outlines how each chapter contributes to our understanding of the dynamics of knowledge growth and the teaching and learning of science.

INTRODUCTION

Given the present demand for change in science instructional practices and science curriculum frameworks—e.g., NSTA's scope and sequence, AAAS's Project 2061—we must ask to what extent teacher educators, teachers, and curriculum writers are being provided with the necessary background knowledge to implement curricula that embrace the intentions of educational researchers and curriculum developers. An important lesson learned from the early attempts at teacher training and curriculum development in science education is the various ways in which teachers can change developers' intended curricula (NSF 1955-1975). Connelley (1972), in a review of science education research, reports that curriculum developers intentions are often lost in the transmission of the curriculum to teachers and thence to students.[2] Research that examines teachers' beliefs about teaching, about students and learning, and about subject matter (i.e., the nature of scientific inquiry) demonstrates that classrooms are extremely complex settings (Tobin & Gallagher 1987; Duschl & Wright 1989; Borko & Shavelson 990). Furthermore, this research suggests that teachers' beliefs do effect the type of instructional activities and tasks that make up the cognitive and psychosocial learning environment of the classroom (Doyle 1986; Tobin & Fraser 1990).

Thus, it is possible, and educationally sound, to differentiate between the intended, implemented, and learned curriculum. Roberts (1980/1986) calls changes across this continuum "the modulation of the curriculum." Attempts to develop an effective curriculum framework must, according to Roberts, allow teachers to see the developer's intentions embodied in curriculum materials. An important element of educational practice, and the one emphasized in this volume, is the role

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teachers play in making decisions about curriculum and instructional activities and tasks.

If it is important to allow teachers to understand a developer's curricula intentions, then it is equally important to clearly represent to curriculum developers teachers' conceptions of both the developers' intentions and the subject matter embodied within the intended curriculum. Current approaches to knowledge representation may be helpful in this regard. Research on expert knowers suggests that they employ two types of knowledge: declarative or domain—specific knowledge and procedural/general strategic knowledge (Perkins & Salomon 1989). The importance of this division of knowledge for understanding teachers' beliefs and curriculum writers' intentions is twofold. At the curriculum development level, attempts to develop science curricula should focus on the strategic knowledge required to adequately use domain specific scientific knowledge. This would entail the identification of general procedures that allow for the acquisition and use of scientific knowledge. At the implementation level, a critical goal of teacher training and student learning should be the acquisition and use of both domain—specific knowledge and generic strategic knowledge (cf, Borko & Shavelson 1990; Alexander & Judy 1988; Derry 1990; Wittrock 1986). A major theme of the current volume is the development and examination of conceptual frameworks that outline the nature of strategic or procedural knowledge within and across scientific domains. Our goal is that these frameworks will establish criteria for teachers and curriculum writers that influence the modulation-of-the-curriculum problem in positive ways.

Current instructional approaches for teaching traditional school subjects to students view learners as active agents in the process of constructing meaning (Resnick & Klofper 1989). The explanatory statements of science—theories—are conceived as having a developmental history which is characterized by continual and ongoing restructuring, modification, and adaptation of knowledge claims as well as investigative methods and aims. Examples of new approaches in science that employ learning frameworks and subject matter frameworks that emphasize knowledge restructuring include:

1. learning cycle[3] (Champagne 1988)
2. the conceptual change teaching model (West & Pines 1985; Anderson & Smith 1986; Roth 1990)
3. the generative learning model (Osborne & Wittrock 1983; Osborne & Freyberg 1985)

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These models of conceptual change teaching make specific assumptions, often unarticulated, about the role of the teacher and the dynamics of classroom instruction. Research that looks at classrooms (Doyle 1983, 1986; Lampert 1984; Leinhardt and Greeno 1986; Sanford 1987, 1984; Tobin & Fraser 1990) indicates that when we examine the dynamics of meaning-making instructional strategies at the level of the classroom we find that very complex cognitive tasks confront both teachers and learners.

Doyle (1986, 1983), for example, in his studies on academic work, has found that teachers' definitions of academic work and students' perceptions of instructional tasks can transform the curriculum in ways that have implications for what students learn in classrooms. Such transformations were particularly common when instructional tasks sought to engage students in higher cognitive tasks involving meaning-making activities. Thus, distinguishing between the intended, the implemented, and the learned curriculum would be helpful in capturing the transformations that occur as students and teachers renegotiate instructional tasks.

New images of the complexity of exemplary teaching are emerging. Tobin and Fraser's (1990) study of exemplary teachers' practices found that the lack of teachers' content knowledge result in an emphasis on learning facts and the development or reinforcement of students' misconceptions. Lampert's (1984, 1986) efforts have examined the way in which teachers can use student intuitive knowledge frameworks as stepping stones to learning the formal knowledge of the curriculum. Here, again the complexity of the cognitive tasks for students and for teachers is apparent. Sanford (1987) found that elaborate instructional devices she refers to as "safety nets" are employed by exemplary teachers to encourage and support higher-level thinking instructional activities and tasks.

Leinhardt and Greeno (1986) have also studied exemplary teacher practice, and their findings indicate that elaborate and complex cognitive tasks are characteristic of instructional moves made by these teachers. It is our opinion that the elusive nature of teaching for conceptual change or the restructuring of students' knowledge is embedded in an underestimation of the cognitive and psychosocial dynamics of classroom environments that teach students to understand both scientific knowledge (what we know) and knowledge about science (how we know). Research by Lampert (1990), Tobin and Gallagher (1987), Duschl and Wright (1989), and Mitman et al. (1987) support this opinion. A serious practical problem, however, is that contemporary reform recommendations (i.e., Project 2061 and the National Science Teachers

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Associations Scope and Sequence Report) that suggest science curricula ought to consider the inclusion of topics that foster meaning-making among students have yet to fully explore the specific procedures and dynamics for implementing a curriculum of this type.

A rapidly emerging consensus among science and math educators holds that education ought to concentrate on fundamental principles that underlie a domain rather than on the numerous facts and procedures that have made up the curriculum for the majority of students (e.g., Duschl 1990a; Lampert 1986; Resnick 1989; Charles & Silver 1988). Duschl (1990a) has argued for the extension of the notion of "principled knowledge" (Lampert 1986) to science, based on the similarity between the structure of scientific theories and the structure of cognitive schemata. The essence of the argument is that epistemological criteria for guiding the testing of theories and for describing the development of theories do exist and, in turn, can be used to format science instruction (Duschl 1990b). Hodson (1988) also endorses the use of philosophy of science to guide the design and implementation of science instruction toward a more philosophically valid curriculum.

The implications for teaching that are consistent with this view are threefold. First, curricular objectives and lesson plans must focus on fundamental principles of scientific understanding. Second, teaching activities that encourage the development of principled understanding need to be developed. Finally, student work should be considered or assessed in terms consistent with this view.

The process of science is one of developing and testing theories to explain phenomena. Students, current science instruction notwithstanding, are natural theory builders. Of course, these theories are often incomplete (e.g., White & Frederiksen 1987), incoherent (e.g., Ranney & Thagard 1988), and misguided (e.g. Caramazza, McCloskey & Green 1981). Science curricula need to be built around the development, testing, and restructuring of scientific theories if students are to "do science," and not simply learn "about science."

A curriculum should foster theory building at the same time that it respects belief systems that are currently held by the student. Often, these theories recapitulate the historical development of scientific thought (e.g., Nersessian 1989; Nussbaum 1983; Thagard 1990). Instructional activities can provide the opportunities whereby students' current conceptions are confronted and challenged, and, through a set of teacher-guided interactions, theories are restructured. Linn (1986), Novak (1977), Novak and Gowin (1984), Resnick (1983), Finley (1983), Anderson and Smith (1986), and Krupa et al. (1985), among others, each speak to the effect a learner's prior knowledge has on subsequent learn-

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ing. The collective body of this research implies that learners, as Carey (1986) asserts, develop their cognitive abilities through the process of progressively changing conceptual schemes.

Scientific thinking, of course, must be grounded in the particulars of a domain. Thus, declarative or domain-specific knowledge related to principles, laws, theories, and generalizations must be taught, along with the procedural/generic strategic knowledge and the conditions of its applicability. Within the context of normal scientific developments or weak restructurings there is a small amount of procedural knowledge to be acquired about the fine tuning of theories and the adjustment of conceptual relations. But if we are to produce radical restructuring of concepts, the personal correlate of revolutionary science, then it seems that we must also teach the procedural knowledge involved in evaluation of theory and data. Duschl, Hamilton, and Grandy (this volume) posit that the nature of such procedural knowledge has been little studied and not at all agreed upon. Moreover, they contend it may well vary greatly from one scientific domain (and epoch) to another! The instructional strategy and design that are employed to teach a unit on the Theory of Evolution or Theory of Plate Tectonics might require a very different set of procedural knowledge guidelines than a unit on biological or mineralogical identification and classification.

The challenge, then, for teachers and curriculum writers is how best to integrate both the declarative knowledge structures and the procedural or strategic knowledge structures of a discipline into the framework of curriculums and into the cognitive and psychosocial characteristics of classroom learning environments. Thus, science teachers and curriculum writers need to consider how teachers' conceptions of subject matter and of learners can assist in making the intended curriculum the implemented curriculum and, in turn, the learned curriculum. A promising strategy to employ is one that draws from both cognitive psychological and epistemological principles. Concomitant with the developments of NSF science curriculum projects (1955-1975) were the equally dynamic developments in the fields of cognitive science, computer science, and history and philosophy of science (Duschl 1985). Today, there is a growing consensus among psychologists (e.g., Carey 1986), philosophers (e.g., Giere 1988; Nersessian 1989), and science educators (e.g., Duschl, Hamilton & Grandy this volume; Hodson 1988) that there exist interfield relationships between history and philosophy of science and cognitive science that can inform science education research and practice. Hodson (1988) describes this symbiotic type relationship as follows:

The view that scientific concepts and theories are subject to mod-

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> ification and growth has a direct counterpart in the assumption . . . that children's conceptual frameworks are continuously modified, refined, and made more precise as they gain in experience and understanding. Thus, acceptance of this view of progressive conceptual differentiation in science and of constructivist views of the nature of learning ensures *harmony* between the philosophical and psychological principles underpinning the curriculum. (P. 28, emphasis added)

AN EMERGING DOMAIN

We find ourselves, then, at a critical and exciting time in science education. It is critical because scholars from distinct disciplines are working at similar types of problems that have relevance for science education research and practice. Separate disciplines that explore a common ground of inquiry, that seek solutions to the same problem, that ask related questions, that draw from a related literature and that share knowledge claims are referred to as "domains." "A domain . . . is not *merely* a body of related information; it is a body of related information about which there is a problem, well defined usually and raised on the basis of specific considerations" (Shapere 1977). The history of science during the twentieth century is one in which the generation of new domains of science has been a commonplace event. Biophysics, fluid dynamics, artificial intelligence, geochemistry, and geophysics are examples of the subfield domains that represent a unified subject matter for scientists trained in separate disciplines.

The spawning of interfield relationships among scholars is certainly not restricted to the above sciences. As mentioned above, since the 1950s advances in philosophy of science, cognitive psychology, and science education have led to the development of a domain that, for lack of any specific label, seeks to understand the dynamics of the growth of scientific knowledge. It is the quest for richer analyses of what constitutes scientific knowledge that has spawned domains relevant to science education researchers and practitioners.

Our edited volume has two purposes. The first is to inform those persons unfamiliar with the "growth of scientific knowledge" domain about the domain and thereby hopefully extend the community of participants. The second is to embellish the dialog among teachers and science education researchers interested in participating in research and practice activities that draw upon epistemological and psychological principles of scientific knowledge growth.

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OVERVIEW OF CHAPTERS

This edited volume draws upon the expertise of scholars in philosophy of science, cognitive psychology, and science education, scholars who share an interest in understanding the dynamics of knowledge growth, to outline the elements of this important emerging domain for educational researchers. It begins with an article by Richard Duschl, Richard Hamilton, and Richard Grandy, a synthesis of views from science education, cognitive psychology, and philosophy of science, respectively. This lead article was prepared to stimulate the interfield developments cited above and to do so by pointing out where the fields of cognitive psychology and philosophy of science were at odds with one another. It is hoped that by drawing attention to the tensions within the domain, progress will be made.

Each of the contributors to this volume was given a copy of the lead article and asked to react to the ideas presented in the lead article within the context of their respective chapters. Care was taken to invite contributors who would represent the breadth as well as the depth of analysis and inquiry taking place in the emerging domain. As indicated in the introduction, a theme that runs throughout chapters within this volume is the importance of the procedures or strategic knowledge required for the acquisition, appropriate use, and modification of scientific knowledge. Instructional implications related to the nature of procedures for knowledge acquisition in the sciences and the factors which influence the use and development of these procedures are presented in the following chapters. A predominantly psychological or epistemological perspective dominates most chapters; however, each chapter represents a blend of these perspectives. As a collection, we feel the volume represents a strong synthesis of relevant research issues and trends.

The task environment of philosophers of science since the 1950s has been to accurately characterize the dynamics of theory change. This scholarly environment has been informed by historians of science and subsequently shaped by the symbiotic relationship between historians of science and philosophers of science. The efforts by philosophers to establish precise normative guidelines for what it is that "counts" as a theory of science—a task of the logical positivists'—have, along with the observational/theoretical distinction, been rejected. What has emerged, in its place, is a commitment to describing actual science as it is practiced, or reported to have been practiced by historians of science, at a level of detail that embraces the dynamics of theory restructuring.

We have chosen to follow the introductory chapters with an inno-

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vative work by a philosopher of science who employs history of science to increase our understanding of the dynamics of theory restructuring. Nancy Nersessian's research and her chapter here, "Constructing and Instructing: The Role of 'Abstraction Techniques' in Creating and Learning Physics," represent a synthesis of history of science, philosophy of science, and cognitive science. What makes her effort different from previous efforts to integrate history of science into science education (e.g., Conant's 1957 Harvard Case Histories in Experimental Science.) is the inclusion of contemporary philosophical and psychological perspectives that focus on knowledge development and restructuring. In this chapter, she argues that the cognitive activities (i.e., "abstraction techniques") of scientists who have constructed new conceptual structures are directly relevant to learning and that understanding these practices will assist us in our efforts to help students construct representations of extant scientific knowledge. That is, we need to investigate (via the history of science) the kinds of procedures employed in the initial construction of conceptual structure and attempt to teach students how to construct these representations for themselves using the same procedures. Students would then not only be made aware of discrepancies in their scientific knowledge, but also be given tools to either restructure their knowledge structures or create new structures.

The next chapter, by Greg Nowak and Paul Thagard is entitled "Newton, Descartes, and Explanatory Coherence" and also represents a synthesis of history of science, philosophy of science. and cognitive science. The authors, however, take a very different approach to the investigation of the history of science. In there chapter, a computational theory of explanatory coherence is applied (via "ECHO" a connectionist computer program) to the conflict between Newtonian mechanics and the Cartesian system of the world. The authors attempt to assess the global coherence of each explanatory system. "Explanatory coherence" can be described as the degree to which propositions of theories are consistent or are interrelated. The successful application of the computational theory to this and other important scientific "revolutions" of the past (cf. Nowak & Thagard in press; Thagard & Nowak 1990, 1988) underscores its usefulness as an efficient means of selecting the best set of explanatory hypotheses and relations within current and past scientific theories. The underlying principles of "explanatory coherence" may be useful in aiding students and teachers to evaluate and compare theories. In this way, students and teachers would have another set of tools by which to evaluate and, perhaps, reconstruct their knowledge of scientific theories.

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Richard Kitchener's contribution to the volume—"Piaget's Genetic Epistemology: Epistemological Implications for Science Education"—focuses on the role of the epistemic subject in the process of knowledge growth. His research over the years has shed new light on the proper interpretation of research derived from Piagetian Theory. Within the epistemic subject we see specific ways in which the principles of cognitive psychology join with epistemological principles. A major implication for science education derived from this chapter is the need to focus on *epistemological* change as well as conceptual change. This requires both the monitoring and development of students' theories of knowledge as well as their ability to reason epistemically. Science curricula should induce students to move from an absolutism view of science to a falibilism (probabilitistic) view of science. The author suggests that a historical approach to science may be the best source for the development of science curriculum with the above aims. Again, we see that the history of science is a valuable source for the development of science education curriculum. It is clear that teachers' theory of knowledge and ability to reason epistemically also need to be monitored and modified. How can we ask science teachers to improve students' ability to reason epistemically if they themselves are at a similar stage or a lower stage of epistemic reasoning (cf., Kitchener & King 1981)?

Those familiar with the literature on conceptual change know that the seminal article on the theoretical foundations of conceptual change is that by Posner et al. (1982). But as with science, change is inevitable and we are pleased to include a chapter by Kenneth A. Strike and George J. Posner—"A Revisionist Theory of Conceptual Change"—which represents a revision of their thoughts about what it is that is necessary to foster conceptual change within learners. It also represents an attempt on their part to address some of the criticisms brought against the model of conceptual change advocated in the 1982 article. Their position is a strong step forward in the scholarly dialog surrounding conceptual change teaching. A central construct in the original theory of conceptual change is a learner's "conceptual ecology." Learners' conceptual ecology consists of their knowledge of anomalies, analogies, metaphors, epistemological beliefs, metaphysical beliefs, and knowledge from other areas of inquiry and knowledge of competing conceptions. The difficulty of changing a learner's misconceptions is partially a function of the degree to which these misconceptions are supported by a learner's conceptual ecology. One suggested change presented in the Revisionist Theory is a proposal to broaden our definition of the range of factors which comprise the learner's conceptual ecology to include psychological factors, that is, learner motives and

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goals. This represents a blending of psychological influences with epistemological factors within a learner's conceptual ecology. An important element of the chapter is the presentation of empirical data in support of the authors' proposed revisions of the original conceptual change framework.

The next chapter, "Contexts of Meaning and Conceptual Integration: How Children Understand and Learn" by Jeffrey Bloom, fits nicely with the Revisionist Theory proposed above, for it is Dr. Bloom's contention that we have underestimated the complexity of children's conceptions about the constructed meanings of science. The research discussed in this chapter sets out the extensiveness of the task science education must undertake, at times in directions not previously considered. Children are viewed as interdisciplinary thinkers, their constructed meanings influenced by a mix of factors, that is, emotions, values, aesthetics, interpretive frameworks, metaphors, and formal and experiential knowledge. To attempt to separate science in a formal way from these multiple contexts of meaning is to ignore the varied nature of childrens' constructed view of the world. The "contexts of meaning" described in this chapter overlap considerably with the extensions of conceptual ecologies proposed in the Revisionist Theory of Conceptual Change. In both cases, a predominantly epistemological view of scientific knowledge is modified in order to incorporate psychological factors and dimensions.

The task environment of cognitive psychologists has increasingly become one that is concerned with learning domain-specific knowledge. The adoption of a view of knowledge and learning that recognizes differences in the declarative knowledge and procedural knowledge employed by individuals working in distinct subject areas has significant implications for others concerned with the structure of knowledge and knowledge restructuring. It isn't surprising, then, to find philosophers examining and integrating the social dimensions and cognitive psychological dimensions into their philosophies of science. The chapter by Stephen P. Norris—"Practical Reasoning in the Production of Scientific Knowledge"—extends the dimensions of this discussion into the area of practical reasoning based on values about what ought to be done. Dr. Norris outlines aspects of scientific knowledge production as well as scientific knowledge acquisition toward the argument that a focus on practical reasoning is central to the epistemic and inquiry frames of understanding. Again, the suggested instructional approach is one that "mines" the history of science and describes the processes and influences on the reasoning (in this context—the practical reasoning) involved in the production of past and current scientific theories.

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The final two chapters of the volume are perhaps the most "psychological" and "applied" treatments of the blending of epistemology, psychology, and science education. Richard Mayer's contribution—"Knowledge and Thought: Mental Models that Support Scientific Reasoning"—examines the epistemological, psychological, and educational aspects of science explanations. According to the author, scientific explanations are best represented within the context of the invention of explicit systems models. The models include a description of the main components of the system, the possible states of each component, the causal relations among state changes in the components, and the principles underlying the causal relations. Illustrations of these models (when presented to learners) provide information that supports scientific reasoning and allows for problem-solving transfer including explanation, prediction, and control. The positions taken in this manuscript are derived from a decade-long research program that has had as its goal the development of insights into how students acquire the explanative knowledge they need to achieve scientific understanding.

Continuing with the practical, the chapter by Robert Sherwood and his colleagues at Vanderbilt University's Cognition and Technology Group—"Anchored Instruction in Science and Mathematics: Theoretical Basis, Developmental Projects, and Initial Research Findings"—puts theory into practice. It is very appropriate that we finish this volume with a chapter that contains the most explicit prescriptions for the development of science curriculum. Over the past several years, the authors of this chapter have been developing the concept of "anchored instruction." Outlined here is their model of anchored instruction which situates science and mathematics in meaningful and authentic contexts.

One of the major goals of anchored instruction is to create shared environments that permit sustained exploration by students and teachers and enable them to understand the kinds of problems and opportunities that experts in various areas encounter and the knowledge these experts use as tools. Students and teachers are exposed to situations which require both problem formulation and problem solving. Participants experience the value of exploring the same setting from multiple perspectives and are encouraged to explore the complex settings from their own perspectives. Embedded in the anchored instruction approach are many of the procedures identified and discussed in early chapters of this volume, for example, analogies, imagistic representation, coherence and consistency, cognitive conflict, importance of motives and goals, illustrative models, and so forth. The research described in this last chapter, then, is a preliminary evaluation of the usefulness of both anchored instruction *and* the procedures outlined by the other authors.

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SUMMARY

Norwood Hanson in his classic book *Patterns of Discovery* (1958) distinguishes between two ways of seeing. The first, "seeing as," is observation that occurs without the benefit of the appropriate background knowledge. The second, "seeing that," involves observations with the appropriate background knowledge. In a sense, the task science educators face is to take individuals who are "seeing as" observers and help them become "seeing that" observers. This is a simplistic but nonetheless accurate version of what it means to engage in conceptual change teaching.

Sounds simple enough—but anyone who has attempted to restructure a learner's knowledge base knows how difficult the task really is. Educators are fortunate, then, that many cognitive psychologists and philosophers of science have involved themselves in activities which seek to understand the procedural and developmental steps aligned with knowledge growth and restructuring. For psychologists the task is one of documenting the dynamics of reasoning. For philosophers the task is one of accurately characterizing the processes of knowledge growth. The former are principally concerned with the activities of individuals, while the latter are concerned with the activities of individuals within communities. But each discipline has a mutual concern for what it is that counts as prototypical evidence (exemplars) and counter evidence (anomalous data) for an individual.

We hope that this volume will bring about a type of "seeing that" conceptual change among science educators in ways that serve to positively affect instructional decision making. Each chapter is organized structurally to facilitate readers' understanding of the implications for science education theory and practice. There is an abstract and an outline at the beginning of each chapter, which provide an overview of the central concepts. But most importantly each author has been asked to generate a summary section that specifically addresses the implications their ideas have for science education researchers and practitioners. We are convinced that individuals who work through the set of readings in this volume will "see that" science education has evolved a great deal over the last thirty years.

NOTES

1. The editors would like to acknowledge Dr. Drew Gitomer, Educational Testing Service, Princeton, NJ, for the contribution he made to the preparation of the overview of science education research section of this chapter.

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2. These results are consistent with the results of research on curriculum implementation in other fields of education as well (See Fullan & Pomfret 1977; Berman & McLaughlin 1976; Waugh & Punch 1987).

3. Champagne's learning cycle, while similar in name to the instructional model developed by Robert Karplus and extended by John Renner, Anthony Lawson, and others, is nonetheless quite different in its intent. Champagne's learning cycle is based on the psychological theories of Vygotsky and Ausubel. The Karplus learning cycle is based on Piagetian Stage Theories of Development.

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