

Cognitive Schema Theory in the Constructivist Debate

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Cognitive constructivism is not a unique theoretical framework, pedagogical approach, or epistemology, but a general, metaphorical assumption about the nature of cognition that virtually all cognitive educational researchers accept. Despite this unifying assumption, there are many different cognitive constructivist research programs and theories within the community at large. This article contrasts cognitive constructivism with several other forms of constructivism in the educational research community. It then attempts to represent the range of theoretical approaches within cognitive constructivism, pointing to examples and potential educational applications of cognitive constructivist ideas. Cognitive schema theory receives special attention as an important theoretical perspective that has been relatively neglected in recent theoretical discussions. It is believed to have significant potential for building conceptual bridges between information processing and radical constructivist viewpoints.

When Mayer (1992) suggested that the knowledge construction metaphor would provide a substantial unifying force for educational research, I (Derry, 1992) questioned whether unification could possibly occur because constructivism was claimed by various epistemological camps that did not accept one another as theoretical comrades. Since then, there have been a great many conference symposia, special journal issues, special small conferences, and edited volumes devoted to the task of explicating similarities and differences among various versions of constructivist educational theory. Collectively, these forums are evidence that both Mayer and I were basically accurate. Ethnocentricity within various constructivisms continues, but a dialogue among them is now progressing in an effort to overcome differences that impede the scientific practice of education.

Finding resolution between forces of division and consolidation within constructivism was a theme in Steffe's (1995) retrospective analysis of a 1992 conference on alternative constructivist epistemologies (Steffe & Gale, 1995). In his introduction to that retrospective, Steffe stated,

My intention is to establish possible relationships among the alternative [constructivist] epistemologies that might not have been considered at the conference and, thereby, to open paths for communication. This amounts to much more than

an academic exercise because there is a lot at stake here for the education of children and young adults, and for the role of constructivism in that education. ... What some might consider to be good ideas often never materialize because they are in conflict with other perhaps equally good ideas—conflicts that can paralyze action, rather than engender modification in action.

(p. 489)

Separation and unification were concerns also expressed in Marshall's instructions to contributors to this special issue. Based on these concerns and the editor's request, I focus my analysis on the topic *cognitive constructivism*. I begin by contrasting the cognitive orientation with other constructivist frameworks. I then attempt to characterize the range of mainstream theories and approaches within the cognitive constructivist community, which encompasses both modern information-processing psychologies and versions of radical constructivism. One thesis of this article is that information-processing psychology and radical constructivism can and should blend their programs together, striving for a more exact science of radical constructivist teaching and learning. To that end, I focus on the connecting concepts of *schema* and *schema change*, important ideas found within many information-processing theories as well as within radical constructivism. I attempt to show why a hierarchical cognitive theory of schema and schema change has interesting potential for building bridges of understanding between information-processing psychology and radical constructivism, thereby advancing the science associated with constructivist theory.

COGNITIVE CONSTRUCTIVISM VERSUS OTHER CONSTRUCTIVISMS

For purposes of this discussion, cognitive constructivism is characterized as a range of psychological perspectives, pertaining to cognitive processes and representations in learning, that can be delineated conveniently by using Phillips's (1995) multidimensional framework for characterizing and comparing constructivist viewpoints. Phillips's framework has three dimensions. The first, described as the "individual psychology" versus "public discipline" (p. 7) continuum, recognizes that some theories are concerned more or less with how the individual learner goes about the construction of knowledge, whereas others are concerned more directly with the construction of human knowledge in general. Cognitive constructivist research and practice as described here is mostly oriented toward understanding the individual learner. This focus is not meant to minimize the importance of and need for theory that connects individual knowledge construction to the evolution of public knowledge, but rather to clarify the purposes and limits of the discussion.

The second dimension relates to the first and differentiates among theorists according to whether they view knowledge construction as a socially situated or an individual process, a dimension related to much recent debate in the cognitive science and educational research communities (e.g., J. R. Anderson, Reder, & Simon, 1996; Vera & Simon, 1993). Driver, Asoko, Leach, Mortimer, and Scott (1994) discussed a similar tension dividing the sociocultural and constructivist programs in science education. Although Driver et al. argued that scientific and mathematics knowledge is socially constructed and that science learning is acculturation, cognitive constructivists have been more concerned with the development of individual understandings. Cobb and Yackel (e.g., Cobb, 1994a, 1994c; Cobb & Yackel, this issue) resolved this tension in their work by advocating a unified viewpoint that combined social, sociocultural, and cognitive constructivist perspectives. They argued that individual cognitive processes and sociocultural ones are mutually implicative and cannot be studied in isolation. Consistent with this idea, the purpose of my discussion is to suggest a way of thinking about the cognitive representations and processes that characterize individual knowledge construction, which is understood to occur in social context. As Cobb and Yackel note, this cognitive constructivist perspective brings individual cognitions to the foreground against a background of social context.

The third dimension differentiates constructivists in terms of the degree to which they can, in essence, be characterized as true constructivist theorists. At one end of this scale is the empiricist position that the mind is shaped by nature in a relatively passive fashion. Epistemology at the empiricist extreme is only a benchmark because it is not really constructivist at all. On the other extreme are the most "radical" (von Glasersfeld, 1990, p. 19) thinkers who hold that all knowledge is perspectival, the result of purposeful activity-based con-

struction on the part of learners. Between these poles are various hybrid information-processing hypotheses that explain thinking in terms of interactions between data-driven environmental influences on the one hand and deliberate, reflective mental construction on the other (e.g., Mayer, this issue; van Dijk & Kintsch, 1983). The area of this scale encompassing information-processing and radical constructivist views, and including many hybrid views in between, identifies the range of viewpoints within mainstream cognitive constructivism today.

In sum, Phillips's framework provides a convenient means of communicating which aspects of constructivism lie within and without the present zone of concern, which pertains to questions about how individual learners represent and construct knowledge, processes I assume are shaped by social context.

EPISTEMOLOGICAL VARIATION WITHIN COGNITIVE CONSTRUCTIVISM

Cognitive constructivism embraces many psychological viewpoints, ranging from models of general cognitive architectures to specific theories about how people reason with mental models to theories about how learning occurs with specific problem types in specific kinds of instructional environments. This section describes three general classes of cognitive constructivist theory that illustrate the range of theoretical variation that exists within mainstream constructivist theory. The theoretical classes overviewed are modern information-processing theory, radical constructivism, and cognitive schema theory. Schema theory may supply a useful conceptual language for bridging between information-processing and radical psychologies. The potential benefits of building such bridges include supporting a more detailed and exact science of constructivist learning and teaching.

Modern Information-Processing Theory

Cognitive constructivism embraces the modern information-processing model that evolved from the "Pittsburgh School" of cognitive psychology, which was highly influential from the 1970s through early 1990s. The article by Mayer in this issue considers this theory, so my section on this perspective will be brief. This theoretical stance is clearly constructivist in orientation, but historically it represented a comparatively weak constructivist hypothesis, leaning toward the conservative end of the degree-of-constructivism scale. Important foci of this work included cognitive modeling of general problem solving, development of domain-specific expertise, and models of general cognitive architectures. Early cognitive studies focused largely on problem solving and emphasized the importance of general problem-solving heuristics, such as means-ends analysis. This research helped inspire and inform

an era of classroom practice based on direct instruction in general problem-solving skills (e.g., Bransford & Stein, 1984). Later work emphasized development of domain-specific expertise and inspired much cognitively guided instructional practice within specific domains (e.g., Bruer, 1993).

The dominant cognitive architectural model (J. R. Anderson, 1983) has evolved, but it continues to describe human memory as having both declarative and procedural (skills) aspects. Declarative knowledge is represented as propositional networks, and skill knowledge is represented as complex collections of if-then statements, called production systems. The concepts of working memory, long-term memory, and an executive controller are central to this view. General learning mechanisms include the processes of elaboration and organization for declarative knowledge, composition and proceduralization for skill learning, and (recently) reflective generalization for all learning. Models of learning and instruction for both declarative knowledge and skills are constructivist in a restrictive sense. For example, skill development requires active student engagement in practice, which results in the gradual building up of a complex production-system memory representing domain-specific expertise. The purpose of training is conceived as moving students toward performance goals represented by expertise.

Information-processing theory continues to supply theoretical grounding for cognitive researchers (e.g., Mayer, this issue) and teacher education (Gagné, Yekovich, & Yekovich, 1993). It continues to serve as the basis for training design in industry, within the military, and for several technology projects that are successfully operating in public schools (see J. R. Anderson, Corbett, Koedinger, & Pelletier, 1995; Derry & Lajoie, 1993). Although instructional applications based on this theoretical stance vary widely, a prototypical example is J. R. Anderson et al.'s computer-based *cognitive tutors*, designed to help students acquire skill in algebra, programming, and geometry-problem solving. Developing a tutor involves conducting cognitive research to specify the expert production-system model for the skill being taught. The expert production system is programmed into the tutor and represents an executable model problem solver. Such models sometimes include common buggy, novice productions, representing misconceptions identified by research in the domain. A human student's performance on the system can then be "diagnosed" by matching each performance step taken by the student to a production that would be executed by the student model under the same conditions. The system determines whether the human student has just performed an expert production or whether the student's move indicates a particular known bug or misconception. Depending on which production in the model is matched by the student's step, appropriate feedback is selected. Feedback directs the student toward the problem-solving move suggested by the expert model. Students are usually not permitted to founder or explore the problem space before they are corrected.

Schofield, Eurich-Fulcer, and Britt (1994) studied the effects of a large-scale implementation of a computer-based geometry intelligent tutor within actual classroom settings. They documented many examples of positive learning and behavior changes for both teachers and students. Compared to students who did not receive instruction with computer-based cognitive tutors, students in cognitive tutor classes exhibited substantially increased motivation. Discipline problems were reduced, and classrooms became more student centered, with teachers shifting away from lecture methods toward roles as facilitators engaged in shared problem solving with students. In some respects, then, this approach has been impressively successful in practice.

Strong Constructivism

At the most constructivist end of the scale is the strong constructivist program, or radical constructivism (Tobin, 1990; von Glasersfeld, 1984; 1990), now a dominant perspective in science and mathematics education communities and an influential force in current educational reform movements. The strong constructivist program evolved from Piaget's genetic epistemology, although neo-Piagetian views may deviate from Piaget's original tenets. Essentially, radical constructivists believe that all new logical-mathematical and conceptual understanding is constructed on the basis of previously constructed schemes. Furthermore, they believe that reflective activity—physical, social, and mental—is the catalyst that brings about cognitive structuring and restructuring.

Students employ their knowledge structures in efforts to construct working understandings of situations they observe and experiment with in the world. This process involves assimilating activity patterns to previously constructed mental schemes, then using these instantiated schemes in problem solving and other thinking. But, if real-world phenomena cannot be understood on the basis of existing knowledge, a state of disequilibrium is created that motivates efforts by the students to adjust knowledge to bring it into greater harmony with observation. From this perspective, opportunities that provoke reflective experimentation, discourse, and negation of conceptual conflicts should be provided. Such environments promote assimilation and accommodation and lead to the construction and reconstruction of knowledge.

Von Glasersfeld (1995, p. 382) wanted teachers to view themselves as midwives who facilitate the birth of understanding, not as engineers of knowledge transfer. He cited two rules of thumbs for teaching. The first is that all understanding comes about through reflection, and reflection is a process that students must carry out for themselves. However, a teacher who understands where a particular student is in his or her conceptual development has a better chance of fostering reflective abstraction than does one who merely follows a curriculum. Second, reflective abstraction always begins on the basis of some form of sensorimotor activity. However, there will never be a program of specific, recommended

activities or manipulations because what promotes reflective abstraction for one student may not work as well for another. However, longitudinal studies of conceptual construction are beginning to furnish a repertoire of potentially facilitatory situations and tasks for instruction.

Radical constructivist epistemology accepts the view that ontological reality is not accessible to rational human knowledge (von Glasersfeld, 1990). Thus, no individually constructed viewpoint is judged as less "correct" than another, although individually constructed perspectives can be judged partly in terms of their alignment with consensually accepted cultural norms. Although it is possible to transmit directly to students the facts and ideas of a particular culture, this form of learning tends to be regarded as trivial (e.g., Cunningham, 1992). Greater value is placed on knowledge construction that is a product of social sense-making processes in which students become engaged, activities involving debate, design, and modeling. Thus, in constructivist classrooms, specific concepts and ideas tend not to be taught directly through explanation but may be "named" as students construct them in the context of work and discussion.

Derry, Levin, and Schauble (1995) recently developed an introductory freshman course in statistical reasoning that exemplified a constructivist educational approach. In the unit on sampling distributions, for example, students were given homework readings on the topic, including reports of how sampling statistics were used to help judge the fairness of hiring practices. In class, students were divided into small groups. Each group was given a large canister filled with colored candies, each color representing a different minority or majority group within a population. The population represented a 5-year pool of applicants to a college program. Students were also supplied with an envelope that contained a sample of candies from their jar, the sample representing those who had been selected over the past 5 years. A flip chart or blackboard was provided, and each group was asked to use the materials supplied to determine whether or not the candies in the envelope were the outcome of a "fair" selection process.

Within two 75-min class periods, most groups devised a procedure that involved repeatedly sampling from the jar, graphing the resulting sampling distribution on their chart, then comparing their envelope sample to the resulting distribution. Ultimately they were able to make a reasoned intuitive judgment as to whether or not the composition of the sample in the envelope was likely to occur under assumptions of unbiased random sampling. Some groups went on to investigate and compute a 2 *SD* criterion for judging sample likelihood.

Before reaching this stage, most groups tried a strategy of counting all the candies in their canister to determine the population composition, but then realized they did not know how to "prove" whether the composition in the envelope was sufficiently different from that in the canister to indicate selection bias. This created an impasse for some groups, leading their instructor to suggest a procedure involving

repeated sampling. For this strategy to be manageable, groups first had to make a simplifying assumption that involved grouping all "minority candies" together then reframing their question to ask whether hiring practices were biased in favor of or against minority candidates as a whole.

During a whole-class discussion following the exercise, groups presented their problems and justified their solution strategies to the class. Different groups had been given different problem variations: The size and composition of the candy populations and samples were varied between groups. This invited comparisons of results, leading to questions and discussion of why some sampling distributions were more "spread out" than others, and why some results were more clear-cut. Through instructor questioning, many students acquired an intuitive sense of statistical power. This was indicated when one group, which had based its repeated sampling procedure on a sample size smaller than the one suggested by their envelope, decided to repeat their procedure using the larger sample size. The group shared with the class a comparison of their two sampling distributions, as well as their conclusion about the improved accuracy of their test based on the larger sample size.

The purpose of this class was to help students develop an intuitive understanding of sampling distributions, as well as how and why such distributions might be used in real-world problem solving. Radical constructivism holds that such understanding can only be constructed through a gradual process of disequilibration and accommodation brought about through reflective physical and social activity, processes that seemingly occurred during our class. Information-processing theorists might argue that equally suitable, perhaps equivalent, constructive mental activity could also be promoted by an effective lecture on sampling distributions or by presenting sampling concepts and problems on an intelligent computer tutor. But to radical constructivists, the lecture or computer-based instruction would represent a transmission view of learning, much less likely to produce the in-depth understandings that can be built up from activity and discussion that engages and challenges prior knowledge.

Claims such as these are interesting and important empirical questions. Questions about what cognitive processes and understandings do or do not result from various learning environments—whether radical constructivist, traditional, or inspired by information-processing theory—should be (a) addressed by appropriately designed, scientific instructional research that focuses on cognitive processing and appropriate learning outcomes and (b) answered primarily on the basis of evidence produced by such research. In addition to qualitative and descriptive research, controlled comparative studies are needed to support or refute any claims for superior instructional environments. And because not all things are possible in all environments, it is important that we study and understand the strengths and weaknesses of the learning that does take place under various instructional practices. But to ad-

vance this research program, a more integrative theoretical language may be needed, one that is compatible with, can be understood by, and will obtain support from both information-processing and radical constructivist communities.

Cognitive Schema Theory

The concepts *schema* and *schema change* are useful boundary concepts for constructivist dialogue because they share reasonably similar meanings across research programs and have been assimilated into the rhetoric of both radical constructivist and information-processing communities. Radical constructivists tend to understand schemas from a Piagetian perspective, focusing research and instruction strongly on one important class of schema—logical-mathematical schemes. These schemas have come to represent the “big ideas” underlying mathematics and science understanding that students must construct for themselves, and they are distinguished from the kinds of cultural knowledge that can easily be transmitted through direct instruction. In this article, this viewpoint is referred to as Piagetian schema theory, although it is understood to include neo-Piagetian views that have somewhat broadened Piaget’s original notions about schemes.

Schema theory from the information-processing perspective is called cognitive schema theory (CST). CST historically was connected to Kantian philosophy (see Marshall, 1995), the Gestalt movement in psychology, and Bartlett’s (1932) treatise on remembering. Judging by citations, it owes surprisingly little to Piagetian theory, although it overlaps with and provides empirical support for various neo-Piagetian views. CST was well represented in various volumes and texts that appeared during the 1970s and early 1980s (e.g., R. C. Anderson, Spiro, & Montague, 1977; Schank & Abelson, 1977; Spiro, Bruce, & Brewer, 1980), during which time it enjoyed a period of prominence and vitality in the United States and was especially visible in the fields of educational psychology, artificial intelligence, and in studies of text and other forms of connected-discourse processing. The concepts *schema* and *schema-based processing* continue as important parts of the modern cognitive-instructional landscape, although other terms are sometimes used for these ideas. For example, recent research conducted from the perspective of cognitive sociology and discourse linguistics employs the term *frame* in reference to a particular type of schema (e.g., Tannen, 1993).

From the CST perspective, *schema* is a general term connoting virtually any memory structure. The purpose of CST is to identify specific cognitive mechanisms that underlie schema construction and revision. Because CST is, in fact, a version of information-processing theory, it embraces a number of its basic tenets and terms. For example, modern CST psychologists believe in long-term memories that store previously learned schemas, and working memories that rep-

resent a person’s span of immediate attention. Thinking and learning take place within working memory, where prior-knowledge schemas are activated in response to environmental input, providing context for interpreting experience and assimilating new knowledge.

At least three different general classes of schemas can be identified in recent cognitive literature. For purposes of this discussion, these three types are called *memory objects*, *mental models*, and *cognitive fields*. All three types of schemas play important, mutually interactive roles in constructivist learning environments, and an adequate constructivist account of learning must include all of them.

Memory objects. The basic component of stored human knowledge is the memory object, a schema type that includes but is not limited to Piagetian logical-mathematical schemes. I make no detailed assumptions about how such objects are characterized in memory, except to assert that various types of representations (e.g., pictorial, declarative, procedural, auditory, emotional, etc.) can be combined to form a single memory object. Individuals develop memory objects associated with the academic disciplines they study (e.g., physics, algebra), with the kinds of social situations they experience (e.g., attending weddings, dining in restaurants), and with various cultures of practice to which they belong (e.g., participating in a gang, being a scientist).

There are different kinds of memory objects. The simplest objects considered here are phenomenological primitives, or *p-prims*, defined (briefly) as basic, intuitive schemas “whose origins are relatively unproblematic, as minimal abstractions of common events” (diSessa, 1993, p. 105). Particularly in early stages of cognitive development, p-prims are weakly organized. DiSessa makes an epistemological claim that development of scientific knowledge represents the gradual reorganizing of p-prims.

A step above p-prims are the more integrated kinds of memory objects hypothesized by Kintsch and Greeno (1985), Marshall (1995), Sweller and Cooper (1985), and others. According to Sweller and Cooper, these objects are schemas that permit people to recognize and classify patterns in the external world so they can respond with appropriate mental or physical actions. Although these schemas represent very basic knowledge, they are complex and structured. For example, Marshall’s arithmetic schemas incorporate many types of knowledge, including visual cues, set relations, mapping and planning procedures, and procedures for constructing arithmetic expressions.

An even higher order type of memory-object schema is the *object family*, a loosely organized collection of ideas that tend to work together in certain types of situations. For example, students taking a statistics test activate and use various statistics ideas to solve problems. Similarly, a tennis player mobilizes her tennis knowledge upon beginning play. Ideas that

cohere in this way are included in the memory-object category because they activate one another and in some ways behave as single memory objects.

Mental models. Mental modeling can be viewed as a process of constructing, testing, and adjusting a mental representation of a complex problem or situation. The goal of mental modeling is to construct an understanding of a phenomenon. The resulting interpretation is a mental model schema. Previously learned schemas (memory objects) provide building blocks for modeling activity, but mental models represent situational understandings that are context dependent and do not exist outside the situation being modeled. Mental model construction involves mapping active memory objects onto components of the real-world phenomenon, then reorganizing and connecting those objects so that together they form a model of the whole situation. This reorganizing and connecting process is a form of problem solving. Once constructed, a mental model may be used as a basis for further reasoning and problem solving, which may give rise to further readjustments to the mental model. If two or more people are required to communicate about a situation, they must each construct a similar mental model of it.

Constructivist teaching techniques often engage students in activities that have as their goal the construction of situational mental models. The sampling distribution instructional activity described earlier is an example of a modeling activity that used concrete props (canisters of candies) to support mental modeling of a statistical sampling problem. However, the connection between mental model construction, which is situationally and contextually bound, and the permanent learning of memory objects is not fully understood. One school of thought is that model-based learning occurs when there is lasting memory reorganization. Through repeated modeling activities in a common domain or context, memory objects used by students to build models gradually form interconnections so that more complex ideas and cognitive systems gradually emerge (e.g., diSessa, 1993).

Cognitive fields. A cognitive field, a third type of schema, is a distributed pattern of memory activation that occurs in response to a particular event (such as a problem posed, a classroom demonstration, a discussion, etc.) that makes certain memory objects more available for use than others. Cognitive fields are very important types of schemas because they mediate between experience and learning. That is, experience triggers activation of the cognitive field, which in turn delineates the memory objects that are readily available for modeling the experience. The cognitive field thus determines what interpretations and understandings of experience are probable. The cognitive field activated in a learning situation also determines which previously existing memory objects and object systems can be modified or updated by an instructional experience.

Many studies of how cognitive fields affect learning were conducted by discourse-processing researchers during the previous 2 decades. The dependent variables in cognitive field research were understanding and memory for text and other connected discourse, where the concepts of understanding and memory were highly intertwined. One important research procedure involved manipulating the cognitive field activated by learners when discourse was processed, examining the effects of such manipulations on discourse comprehension and memory (e.g., R. C. Anderson et al., 1977; Bransford & Johnson, 1972; Sulin & Dooling, 1974). With this method, an interpretive cognitive field is invoked before discourse is presented by showing subjects a picture, mentioning a familiar theme, or selecting subjects on the basis of their strong prior knowledge in some subject. Over many studies, substantial experimental information accrued concerning specific cognitive mechanisms whereby prior knowledge and experience are integrated in memory (e.g., diSibio, 1982).

Work of this genre confirmed that interpretation and later recall of experience is strongly influenced by background, domain, situational, and world knowledge activated in the learner's cognitive field. The interpretive dominance of the cognitive field was found to increase as discourse became difficult or ambiguous. In fact, if learners' active cognitive fields did not supply an interpretive context prior to presentation of instruction, difficult or ambiguous lessons were not understood or learned. In brief, when events in the world are incomplete so that standing alone they make little sense, they are "filled in" by learners' sense-making efforts, which cause ideas from the active cognitive field to be imported into event memories. The psychological processes of inference, elaboration, and rationalization are used to integrate the subject discourse with the active cognitive field, and these additionally generated elaborations become part of the interpretation and memory for the discourse.

Work in this paradigm was dismissed by some educational researchers because much of it was conducted with ambiguous or bizarre discourse (e.g., Meyer, 1977). Good instructional materials and presentations should generally strive for clarity, structure, and reliability, but the biasing effect of prior knowledge often becomes less obvious as the material being processed becomes more structured, reliable, and less ambiguous. However, science educators found that students' preconceptions can influence students' understanding of science instruction even when presentations strive to be clear and unambiguous (e.g., Roth & Anderson, 1988). Moreover, constructivist classroom teachers frequently build instruction around problem tasks that deliberately do not have obvious interpretations or immediate answers (e.g., Hammer, 1996). Results of cognitive field research are therefore relevant to current instructional issues.

Schema types: A summary. CST as described here holds that learning involves constructing three types of schemas that interact during the learning process: memory objects,

mental models, and cognitive fields. Memory-object schemas represent the permanent results of learning that are stored in memory and thus constitute the population of all preconceptions that a student might use to interpret any event. Cognitive fields represent the situationally activated preconceptions that are likely to be called on during the mental modeling process, before those preconceptions are deliberately organized into event interpretations. Mental models are particular organizations of memory objects that constitute a specific event interpretation.

Instructional example interpreted with schema theory. The following example illustrates the usefulness of CST for understanding instruction. One of my graduate students (Helen Osana) recently helped middle school students develop their abilities to reason about realistic news stories reporting scientific findings (e.g., a story about a new acne medication). Stories provided incomplete or ambiguous data and sometimes drew inappropriate conclusions not supported by evidence. Her method used mentors to direct small-group activities in which there were interpretive and critical discussions of the news stories. Mentors encouraged students to activate appropriate interpretive cognitive fields containing target memory objects—certain statistical and critical-thinking concepts to which students were exposed in previous instruction. During discussions of news articles, students were encouraged to examine what statistical inferences could or could not be made with the statistical information given in the news story, and to analyze and question the writers' and other students' arguments about the story's meaning. Mentors thus guided students in constructing appropriate mental models of news stories, models elaborated with inferences about the strengths and weaknesses of each story's argument. Through repeated activation of statistical knowledge and repeated appropriate use of that knowledge in the modeling of news-story arguments, students were expected to learn in the following ways:

1. When these students encounter scientific news stories in the future, the propensity to activate statistical and critical-thinking ideas as part of their cognitive fields should be significantly greater after instruction, increasing the probability that statistical and critical-thinking knowledge will be used in evaluating scientific news.

2. Previous direct instruction had left behind permanent memory objects, but those memories were likely incomplete or inaccurate understandings of statistical and argumentation concepts. Weak conceptual structures and misconceptions presumably were identified and changed during discussions, a form of learning that will be discussed further in a subsequent section.

3. Over a series of discussion tasks, patterns of cognitive activation associated with the process of building evaluative statistical models of scientific news stories were hopefully strengthened. New object-family schemas should enable students to deal more effectively with object-family news reports and statistical issues that arise in the news.

In sum, viewing this instructional activity in terms of CST clarified the goals of the instruction and significantly shaped actual classroom practice and the design of the materials.

Promoting Schema Change: Resolving Different Viewpoints

Most educational and cognitive psychologists today believe that *all* meaningful learning is a form of active knowledge construction in the sense expressed by Eisenhart and Borko (1991):

A key assumption about student thinking is that learners play an active role in acquiring new knowledge. They actively mediate between teachers' actions and their own learning during classroom instruction. Learning occurs as they make sense of instructional events by using their existing cognitive structures to interpret environmental stimuli. It also occurs as they modify and elaborate their knowledge structures through a process of adaptation to the environment. (p. 142)

So far my discussion has focused mostly on the different types of cognitive structures that are created during learning and how these structures are used to make sense of instruction. The focus in the following section is on the process of adaptive accommodation.

Questions about how students change their minds are of central importance and interest to constructivist teachers and researchers. Studies of belief change, conceptual change, developmental ability change, and memory reconstruction all seek to understand mechanisms whereby mind change can be encouraged through intervention. Currently, two explanations for conceptual change are being debated in constructivist terms within the science education community. A third explanation that sheds further light on the process of mind change is derived from the verbal learning branch of schema theory. These three views are brought into better focus when discussed in light of a CST that posits different types of schemas. In particular, it is helpful to raise the question of which types of schemas are being targeted by different schema-change approaches.

Changing misconceptions. When active cognitive fields supply "suitable" interpretive schemas for instructional tasks or discourse, their role is to facilitate processing, especially if tasks are difficult, ambiguous, or represent problems

to be solved. However, science education researchers in particular have been concerned with changing and improving the conceptual systems that learners activate as a basis for interpreting their world. As science educators see it, the dilemma is that students possess naive belief systems about the physical world that may be highly resistant to change. How to design unambiguous instructional experiences that will bring about adaptive accommodation within basic systems of scientific understanding has been a major thrust of recent research focusing on conceptual change. Conceptual change research aims to understand the cognitive mechanisms that promote conceptual change and to develop principles for instruction that will bring about such change.

An instructional research paradigm associated with conceptual change research is the use of anomalous data to challenge students' belief systems. Chinn and Brewer (1993) discussed this literature in detail, examining how students respond cognitively when such challenges are presented as science instruction. Studies showed that students muster many strategies for protecting their preinstructional conceptions. Protective strategies include discounting or ignoring anomalous data, and compartmentalizing new disconfirming information in memory so that it does not interact with challenged prior knowledge. Students sometimes respond to anomalous data by making minor belief changes, leaving their core theories intact. Rapid, drastic change to important core beliefs is relatively rare and difficult to achieve.

A problem with such conceptual change research and instruction, however, is its failure to clarify what kinds of schemas are being targeted for change. Some studies appear to be targeting entire belief systems, such as might be contained in memory-object families. Others appear to target more precise memory-object concepts. Others appear to challenge particular phenomenological interpretations, or mental models, in the hope that by doing so, faulty beliefs or belief systems stored in memory will also change. Finally, some studies appear to be focusing on student propensities: One might want students to start activating Concept X (instead of Concept Y) for explaining Situation Z. Due to a lack of clarity in conceptual change research about what exactly is changing, it is difficult to draw across-study generalizations about cognitive change mechanisms.

Misconceptions versus p-prims. A current debate on the mechanisms of developmental mind change pits diSessa's p-prims view against the conceptual change approach (Hammer, 1996). DiSessa's (e.g., 1993) alternative view is that students begin physics instruction possessing a number of loosely organized primitive memory objects (p-prims) representing basic intuitive ideas about the physical world, and that all scientific understanding evolves through a gradual reorganization of these. Thus, students are not viewed as possessing stable belief systems that need to be challenged, but as gradually building up organization among loosely organized

primitives. DiSessa points out that primitive memory objects serve as valuable resources for communicating and helping students understand science and are fundamentally "correct." P-prims may be inappropriately applied and combined by students in their attempts to model a particular problem or event, and an unacceptable mental model might result. But this situationally specific misuse of knowledge does not exemplify a fundamental misconception that is stored in memory. As expressed by Hammer, "Not all thoughts students express need to be understood as directly reflecting stable, stored knowledge structures. What the misconceptions perspective treats as a stored construct may alternatively be viewed as an act of construction" (p. 102).

Hammer (1996) articulated this argument and described in detail how both points of view were active within his personal cognitive field and thus informed his thinking as a teacher as he mentally modeled and guided students' classroom discussions. He noted that both views were helpful, although the misconceptions view seemed slightly more so. However, Hammer argued that there may be ways to understand misconceptions as robust but inappropriate patterns of p-prim activation. This, he noted, would constitute a theoretical memory model with multiple levels of cognitive structure.

In fact, CST, as conceptualized here, does provide a multiple-levels theory of cognition that is compatible with both schema-change views previously described, suggesting that both types of adaptive learning take place. With respect to uniting p-prims with misconceptions, the CST explanation is as follows: Memory objects begin as p-prims. Constructive learning processes involve (a) activating cognitive fields that include certain p-prims, then (b) using selected p-prims to construct models of experience. This suggests the route through which p-prims might gradually become reorganized into stable higher order patterns of activation (more complex memory objects and object families). If similar kinds of problems and situations are often repeated for the student, organization will gradually emerge because memory objects that often work together to perform similar classes of tasks tend to acquire stability as a group and activate one another. This process also suggests the route through which stable misconceptions and belief systems can form. Some stable patterns that develop might in fact represent inappropriate interpretations that are repeatedly activated under similar conditions. Once developed, these might need to be challenged deliberately with anomalous data so that disequilibrium and accommodation will occur. In this scenario, the specific type of schema being targeted for change would probably be the activation pattern triggered by certain situations, or the cognitive field.

Gradual schema change. Although dramatic, rapid belief shifts appear to occur under certain conditions (e.g., Spiro, 1977), revolutionary shifts in school are probably not

common. School is largely about fostering gradual schema shifts, or developmental change over time. Insights regarding mechanisms of gradual schema change can be gleaned from Bartlett (1932), who studied story memory over long periods. A current revival of interest in these studies has been accompanied by a new release of his best known work, *Remembering* (Bartlett, 1932). Bartlett viewed story memories as dynamic, changing schemas comprising loosely structured collections of ideas. It is interesting to note, this description is not drastically different from diSessa's (1993) view of developing scientific knowledge systems. Bartlett argued that when students were asked to recall a story, they used their schemas as a basis for reconstructing story events that were not actually present in memory, often due to forgetting processes. Story "reconstruction" was effortful and often imported inferences and ideas from students' recent lives. Bartlett's data showed that inferences and importations generated by remembering were permanently incorporated into the schema such that beliefs about stories were drastically altered after many recollections.

To relate Bartlett's (1932) work to schema change in science or mathematics instruction, one must imagine a loosely structured memory-object family, Schema X, that contains a collection of ideas associated with a scientific or mathematics concept (such as gravity or correlation) or information (such as the "story" of the rain cycle). How might a relatively disorganized, naive schema gradually become altered over time by instructional experience so that it eventually supports more expert analyses and understandings? Bartlett suggested that schema development requires that students repeatedly activate and think about Schema X in the context of (instructional) experiences. Although this point may seem obvious, it emphasizes the issue that students often compartmentalize new instruction so that neither Schema X nor any other prior knowledge can be updated or changed by it. It also suggests that in order for change to occur, the instructional experience must achieve dominance over students' interpretations.

For example, in the middle school classes on critical interpretation of scientific news articles, students were repeatedly reminded by mentors to recall statistics knowledge to help them interpret news articles. Thus, memory objects associated with statistics were active in students' cognitive fields. But because these memory objects, gleaned from lectures and readings, were at first vague and ill formed, they did not provide sufficient interpretive support for building models of the arguments in articles. Thus, the mentored discussion about the articles, and not the students' cognitive fields, became the dominant interpretive force. Improvement over time in students' statistical understandings and use of those understandings indicate that inferences and ideas suggested during discussions were used to fill in gaps that existed in students' active cognitive fields, permanently up-

dating usable statistics knowledge. This is the reversal of the case in which prior knowledge supplies the interpretive context for new experience.

Bartlett's views of schema change are not incompatible with views of radical constructivists, who believe students must reflect on the fit of new experience to currently activated logical-mathematical structures. Conflicts in fit create disequilibrium and bring about developmental changes within those structures. However, Bartlett's data suggest in addition that schema change can be a more passive, gradual drift that depends largely on such factors as the loose, vague organization of prior knowledge, memory dominance of recent over past experience, and the clarity and organization of instructional experience. Thus, schema change does not always require deep reflection, direct challenges to prior beliefs, or feelings of disequilibrium. It requires both the activation of relevant cognitive fields plus introduction of useful, understandable information at critical times during the model-construction process.

This analysis suggests that one condition of continuous intellectual development is that developing schemas be activated and used frequently. An example of change to a relevant, reusable schema is illustrated by the student who processes science instruction about physiology or nutrition by selecting out certain information of interest and using it as a basis for altering a training schema, which determines how the student trains for field sports. Contrast this with the case in which a student acquires, through reading text, a new schematic memory for the terms and concepts pertaining to physiology that might be on a science test. Later, when the corrected test is returned, the student realizes that a misunderstanding has occurred during reading and adjusts the new physiology schema to reflect this correction. During later classroom activities, further development and maturation of the schema occurs. Then, the schema is mentally filed away forever as "school science knowledge."

That students actually use reading strategies designed to help them avoid connecting school information to personally meaningful prior knowledge was illustrated in a study by Roth (1986). Spiro (1977) speculated that such strategies are common and are reinforced by testing practices that require recall of text details. If rewarded for retention of unaltered text information, students learn quickly that relating new information to prior knowledge and their lives in general is unwise because it leads to the loss of required detail and to selective alteration of new information. Although radical constructivism eschews such testing methods, some radical constructivist programs share a similar dilemma because they are so highly discipline based. The educational goal of developing within-discipline schemas is somewhat at odds with the goals of building connections among disciplines or making science, mathematics, and other subject-matter learning highly relevant to students' lives beyond school.

Constructivist Theories: Continuing the Conversation

Cognitive constructivism has been presented not as a unique theoretical framework, pedagogical approach, or epistemology, but as a general, metaphorical assumption about the nature of cognition that virtually all cognitive researchers today accept as truth. There are many different constructivist research programs and theories within the cognitive community at large, and many differences among them. Some of these differences represent an interesting diversity of specialties that is affable and potentially productive; but some represent tensions that are best resolved.

My analysis explored the idea that a hierarchical version of schema theory might have potential for reducing differences by providing common ground for researchers from the two major theoretical orientations within cognitive constructivism: radical constructivism and information-processing theory. These orientations currently differ in a great many ways. For instance, radical constructivists, who represent a major force within the mathematics and science education communities, are deeply influenced by Piagetian theory; whereas information-processing theorists, who tend to be psychologists, find historical roots in both associationism and Gestalt psychology. Another noticeable difference is that radical constructivists tend to be more aware of and reflective about their philosophical and epistemological orientations than are information-processing theorists, who tend to make fewer philosophical statements in their work. Radical constructivists clearly promote certain "political agendas" with respect to educational reform and advocate particular instructional techniques that are consistent with their political point of view. Information-processing theorists, as a group, seem noticeably less interested in the advocacy politics of educational reform but are interested in developing and testing theory about cognitive processes and representations in learning and in studying a wide range of learning environments and learning outcomes from an objective, scientific point of view. Finally, radical constructivists tend to rely more exclusively on observational and qualitative research techniques and are seemingly less concerned with experimental comparison and control than are information-processing psychologists, who continue to view qualitative and ethnographic techniques as integral parts of a scientific research program that must also include controlled experiments, including laboratory experiments, to help determine cause and effect and examine cognitive, and even neural, processing in depth.

In addition to these important differences, however, there also seem to be differences of a "red herring" variety in that they are not really theoretical differences at all, although they may seem so. These include difficulties with cross-cultural communication that can be attributed largely to language conventions; communication difficulties attributable to working at different grain sizes, or levels of analysis, with respect

to cognitive processes; and differences that are due to a lack of integration or as-yet-unresolved dialectics among different theoretical perspectives.

Cross-cultural communication. I recently overheard a colorful cafeteria dialogue between an eminent philosopher cognitive scientist (PCS) and an educational cognitive scientist (ECS).¹ Paraphrased, it illustrates the nature of interdisciplinary forces that divide constructivisms:

PCS: Yes, I connect my work to educational practice, but that is sometimes thwarted. For example, I recently submitted a reflective piece to an education journal, explaining what I thought were relevant, interesting findings from a line of laboratory experimentation and illustrating how these findings had implication in my niece's eighth-grade classroom, with which I was recently involved. It seems that every time I used words like *read* or *say* in that piece, either an editor or reviewer would cross them out and write, "*transmission model!*" What does *transmission model!* signify to you?

ECS: [chuckle] Well, that particular journal may have a radical constructivist bent, an appreciation for activity-based instruction. Other approaches might be viewed as attempts to transmit information or cultural norms rather than help kids construct meanings. Perhaps they interpreted your analysis as representing support for a knowledge-transmission metaphor.

PCS: [reflective pause, chuckle] Doesn't that strike you as a little absurd, what with my being the Immanuel Kant Professor of Philosophy at a "respected" [hyperbolic understatement] institution of higher learning? Really, now, I, and my academic ancestors, were constructivist when constructivist was not cool.

The question begged by this example is, To what extent are divisions among major constructivist perspectives, such as those named in this and other discussion forums, differences associated with chasms between philosophical or pedagogical belief systems, or with less fundamental but nonetheless troublesome difficulties inherent in communicating across disciplinary and professional cultures? A case in point is a terminology difference between CST and radical constructivism that has sometimes caused great difficulty. Radical constructivists view assimilation and accommodation as different aspects of a developmental learning process called knowledge construction. Construction, in schema-theory terms, often means that prior knowledge is serving some role in helping one interpret present experience and is closely connected to the Piagetian notion of assimilation. Schema change, in schema-theory language, is *reconstruction*, not *construction* (e.g., diSibio, 1982; Spiro, 1977). Reconstruction assumes that prior knowledge is being rebuilt on the basis of present evidence and is related to the Piagetian concept of accommodation.

¹Fiction inspired by an actual event.

As this example helps illustrate, it is very important to keep in mind that different language conventions do not necessarily signal fundamentally arguable issues, although they can and do create misunderstandings that produce arguments.

Levels of analysis differences. We also must ask to what extent disagreements among constructivist communities represent differences that are better described as variations in hierarchical levels of analysis as opposed to epistemological disputes related to practice. This question pertains to the widening chasm between so-called laboratory analyses conducted by some information-processing psychologists versus both real-world classroom practice and field-based research performed by researchers who study classroom practice. This is not to say that laboratory research is inherently good. Nor is it a failure to recognize that classroom cognitions are constituted by social interaction, or that the interactions of laboratory research settings differ drastically from those within classroom cultures. But it is an assertion that detailed understanding of cognitive processes is an important part of our scientific knowledge base about teaching and learning, as well as a recognition that it is extremely difficult, if not impossible, to carry out fieldwork in educational settings in ways that can achieve a sufficiently detailed account of the processes and knowledge underlying constructivist teaching and learning. This point is essentially Scribner's (1984), who described how laboratory procedures enhanced field-based research on problem solving in work environments: "It is questionable whether process models of practical problem solving can be developed without reiterative cycles of both laboratory- and non laboratory-based studies" (p. 37).

If education is a learning science, and I believe it to be so, then educators may no more divorce their practice from basic research on cognitive and neural processes than can medical doctors and public health personnel divorce theirs from basic laboratory findings. This is currently an important issue within the cognitive constructivist community in particular because much relevant work in this tradition has and will continue to take place within the laboratory; however, its connection with radical constructivist and social practice views of research are strained. It is between the laboratory cognitive constructivist researcher and the classroom cognitive constructivist researcher that some of our greatest gaps still exist.

Unresolved dialectics. Another issue of importance is the extent to which differences among theoretical perspectives, both within cognitive constructivism and between cognitive constructivism and other constructivisms, represent as-yet-unresolved dialectical arguments that are constantly moving us from old to new. For example, there is an ever-increasing recognition of the need to better define the relation between the social and the individual, although the manner in which that relation is conceptualized is highly influenced by

disciplinary perspective, including language. Many cognitive constructivists today have their roots in information-processing psychology, Piagetian psychology, or both, retaining many principles from those approaches. But they are in the process of evolving toward a theoretical perspective that integrates sociocultural theories as well. For example, in the reported history of Cobb's thinking (e.g., Cobb, 1994b; Cobb & Yackel, this issue), we see first a rapprochement between radical constructivist and information-processing views, then a dialectic integration of this unified cognitive perspective with social and sociocultural approaches. Constructivist viewpoints once at odds are increasingly seeking ways to merge and combine to form stronger theories that are not only more inclusive in the kinds of learning and interactions they explain, but that promote deeper and more detailed analyses of human development and supply different but mutually compatible routes into the study of complex sociocognitive systems such as those encountered in educational environments.

REFERENCES

- Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.
- Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995). Cognitive tutors: Lessons learned. *Journal of the Learning Sciences*, 4, 167-207.
- Anderson, J. R., Reder, L. M., & Simon, H. A. (1996). Situated learning and education. *Educational Researcher*, 25(4), 5-11.
- Anderson, R. C., Spiro, R. J., & Montague, W. E. (Eds.). (1977). *Schooling and the acquisition of knowledge*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Bartlett, F. C. (1932). *Remembering: A study in experimental and social psychology*. New York: Cambridge University Press.
- Bransford, J. D., & Johnson, M. K. (1972). Contextual prerequisites for understanding: Some investigations of comprehension and recall. *Journal of Verbal Learning and Verbal Behavior*, 11, 717-726.
- Bransford, J. D., & Stein, B. S. (1984). *The ideal problem solver: A guide for improving thinking, learning, and creativity* (2nd ed.). New York: Freeman.
- Bruer, J. T. (1993). *Schools for thought*. Cambridge, MA: MIT Press.
- Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research*, 63, pp. 1-49.
- Cobb, P. (1994a). Constructivism in mathematics and science education. *Educational Researcher*, 23(7), 4.
- Cobb, P. (1994b, September). *Theories of mathematical learning and constructivism: A personal view*. Paper presented at the symposium on Trends and Perspective in Mathematics Education, Institute for Mathematics, University of Klagenfurt, Austria.
- Cobb, P. (1994c). Where is the mind? Constructivist and sociocultural perspectives on mathematical development. *Educational Researcher*, 23(7), 13-20.
- Cunningham, D. J. (1992). Beyond educational psychology: Steps toward an educational semiotic. *Educational Psychology Review*, 4, 165-194.
- Derry, S. J. (1992). Beyond symbolic processing: Expanding horizons for educational psychology. *Journal of Educational Psychology*, 84, 413-418.

- Derry, S. J., & Lajoie, S. P. (1993). A middle camp for (un)intelligent instructional computing: An introduction. In S. P. Lajoie & S. J. Derry (Eds.), *Computers as cognitive tools* (pp. 1-14). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Derry, S. J., Levin, J. R., & Schauble, L. (1995). Stimulating statistical thinking through situated simulations. *Teaching of Psychology*, 22, 51-56.
- diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10, 105-225.
- diSibio, M. (1982). Memory for connected discourse: A constructivist view. *Review of Educational Research*, 52, 149-174.
- Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher*, 23(7), 5-12.
- Eisenhart, M. A., & Borko, H. (1991). In search of an interdisciplinary collaborative design for studying teacher education. *Teaching and Teacher Education*, 7, 137-157.
- Gagné, E. D., Yekovich, C. W., & Yekovich, F. R. (1993). *The cognitive psychology of school learning* (2nd ed.). New York: Harper Collins College Publishers.
- Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *Journal of the Learning Sciences*, 5, 97-128.
- Kintsch, W., & Greeno, J. G. (1985). Understanding and solving word arithmetic problems. *Psychological Review*, 92, 109-129.
- Marshall, S. P. (1995). *Schemas in problem solving*. New York: Cambridge University Press.
- Mayer, R. E. (1992). Cognition and instruction: Their historic meeting within educational psychology. *Journal of Educational Psychology*, 84, 405-412.
- Meyer, B. J. F. (1977). The structure of prose: Effects on learning and memory and implications for educational practice. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge* (pp. 137-166). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Phillips, D. C. (1995). The good, the bad, the ugly: The many faces of constructivism. *Educational Researcher*, 24(7), 5-12.
- Roth, K. J. (1986). *Conceptual-change learning and student processing of science texts* (Research Series No. 167). East Lansing: Michigan State University, The Institute for Research on Teaching.
- Roth, K. J., & Anderson, C. (1988). Promoting conceptual change learning from science textbooks. In P. Ramsden (Ed.), *Improving learning: New perspectives* (pp. 109-141). London: Kogan Page.
- Schank, R. C., & Abelson, R. (1977). *Scripts, plans, goals and understanding*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Schofield, J. W., Eurich-Fulcer, R., & Britt, C. (1994). Teachers, computer tutors, and teaching: The artificially intelligent tutor as an agent for classroom change. *American Educational Research Journal*, 31, 579-607.
- Scribner, S. (1984). Studying working intelligence. In M. Rogoff & J. Lave (Eds.), *Everyday cognition: Its development in social context* (pp. 9-28). Cambridge, MA: Harvard University Press.
- Spiro, R. (1977). Remembering information from text: The "state of schema" approach. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge* (pp. 137-166). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Spiro, R. J., Bruce, B., & Brewer, W. F. (Eds.). (1980). *Theoretical issues in reading comprehension*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Steffe, L. P. (1995). Alternative epistemologies: An educator's perspective. In L. P. Steffe & J. Gale (Eds.), *Constructivism in education* (pp. 489-524). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Steffe, L. P., & Gale, J. (Eds.). (1995). *Constructivism in education*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Sulin, R. A., & Dooling, D. J. (1974). Intrusion of a thematic idea in retention of prose. *Journal of Experimental Psychology*, 102, 255-262.
- Sweller, J., & Cooper, G. (1985). The use of worked examples as a substitute for problem solving in learning algebra. *Cognition and Instruction*, 2, 59-89.
- Tannen, D. (Ed.). (1993). *Framing in discourse*. New York: Oxford University Press.
- Tobin, K. (1990, April). *Metaphors in the construction of teacher knowledge*. Address presented at the annual meeting of the American Educational Research Association, Boston.
- van Dijk, T. A., & Kintsch, W. (1983). *Strategies of discourse comprehension*. San Diego, CA: Academic.
- Vera, A. H., & Simon, H. A. (1993). Situated action: A symbolic interpretation. *Cognitive Science*, 17, 7-48.
- von Glasersfeld, E. (1984). An introduction to radical constructivism. In P. Watzlawick (Ed.), *The invented reality* (pp. 17-40). New York: Norton.
- von Glasersfeld, E. (1990). An exposition of constructivism: Why some like it radical. In R. B. Davis, C. A. Maher, & N. Noddings, Constructivist views on the teaching and learning of mathematics. *Journal for Research in Mathematics Education: Monograph 4*, 19-30.
- von Glasersfeld, E. (1995). Sensory experience, abstraction, and teaching. In L. P. Steffe & J. Gale (Eds.), *Constructivism in education* (pp. 369-383). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.