Research in Science Education (2006) 36: 111–139
DOI: 10.1007/s11165-005-3917-8

Promoting Self-Regulation in Science Education: Metacognition as Part of a Broader Perspective on Learning

Gregory Schraw, Kent J. Crippen and Kendall Hartley
University of Nevada

Abstract

The purpose of this article is to review recent research on self-regulated learning and discuss the implications of this research for science education. We draw on examples of self-regulated learning from the science education literature to summarise and illustrate effective instructional methods and the development of metacognitive understanding (Gunstone; 1999a; Rickey & Stacy, 2000; White & Mitchell, 1994). We also focus on the crucial role that metacognition plays in self-regulation (Baird & White, 1996; Nichols, Tippins, & Wieseman, 1997; White, 1998).

We divide our discussion into two main parts. The first focuses on three components of self-regulated learning, including cognition, metacognition, and motivation. We relate these aspects of self-regulation to current practices in science education. The second section focuses on six general instructional strategies for improving self-regulation in the science classroom. We focus on the use of inquiry based learning, the role of collaborative support, strategy and problem solving instruction, the construction of mental models, the use of technology to support learning, and the role of personal beliefs such as self-efficacy and epistemological world views. These instructional strategies are selected because they reflect extensive research agendas over the last decade within the science education literature and are essential to metacognition and self-regulation (Butler & Winne, 1995; Gunstone, 1999b).

Key Words:

Self-Regulated Learning Theory: The Role of Cognition, Metacognition, and Motivation

Self-regulated learning refers to our ability to understand and control our learning environments. To do so, we must set goals, select strategies that help us achieve these goals, implement those strategies, and monitor our progress towards our goals (Schunk, 1996). Few students are fully self-regulated; however, those with better self-regulation skills typically learn more with less effort and report higher levels of academic satisfaction (Pintrich, 2000; Zimmerman, 2000).

Self-regulated learning theory has a distinguished history in cognitive psychology, with its origins dating back to the social-cognitive learning theory of Albert Bandura. At the heart of Bandura’s theory is the idea of reciprocal determinism which suggests that learning is the result of personal, environmental, and behavioural factors.

Personal factors include a learner's beliefs and attitudes that affect learning and behaviour. Environmental factors include the quality of instruction, teacher feedback, access to information, and help from peers and parents. Behavioural factors include the effects of prior performance. Reciprocal determinism states that each of these three factors affects the other two factors.

During the past two decades, researchers have applied Bandura's (1997) social-cognitive theory to many settings, including school learning. These attempts led to the development of self-regulated learning theory which contends that learning is governed by a variety of interacting cognitive, metacognitive, and motivational components (Butler & Winne, 1995; Zimmerman, 2000). Social-cognitive perspectives of self-regulated learning postulate that individuals learn to become self-regulated by advancing through four levels of development: observational, imitative, self-controlled, and self-regulated levels (Schunk, 1996; Zimmerman, 2000). Learning at the observational level focuses on modeling, whereas learning at the imitative level focuses on social guidance and feedback. Both of these levels emphasise a reliance on external social factors. In contrast, as students develop they rely increasingly on internal, self-regulatory skills. At the self-controlled level, students construct internal standards for acceptable performance and become self-reinforcing via positive self-talk and feedback. At the self-regulatory level, individuals possess strong self-efficacy beliefs, as well as a large repertoire of cognitive strategies, that enable them to self-regulate their learning.

Self-regulated learning consists of three main components: cognition, metacognition, and motivation. Cognition includes skills necessary to encode, memorise, and recall information. Metacognition includes skills that enable learners to understand and monitor their cognitive processes. Motivation includes beliefs and attitudes that affect the use and development of cognitive and metacognitive skills. Each of these three components is necessary, but not sufficient, for self-regulation. For example, those who possess cognitive skills but are unmotivated to use them do not achieve at the same level of performance as individuals who possess skills and are motivated to use them (Zimmerman, 2000). Similarly, those who are motivated, but do not possess the necessary cognitive and metacognitive skills, often fail to achieve high levels of self-regulation.

The three main components of self-regulation can be further subdivided into the subcomponents shown in Figure 1. We describe briefly each of these components below, as well as several finer-grained subcomponents.

Cognition

The cognitive component includes three general types of learning skills, which we refer to as cognitive strategies, problem solving strategies, and critical thinking skills. Cognitive strategies include a wide variety of individual tactics that students and instructors use to improve learning. One example is the use of student-generated questions before or during reading to focus the learner's attention (Chinn & Brown,

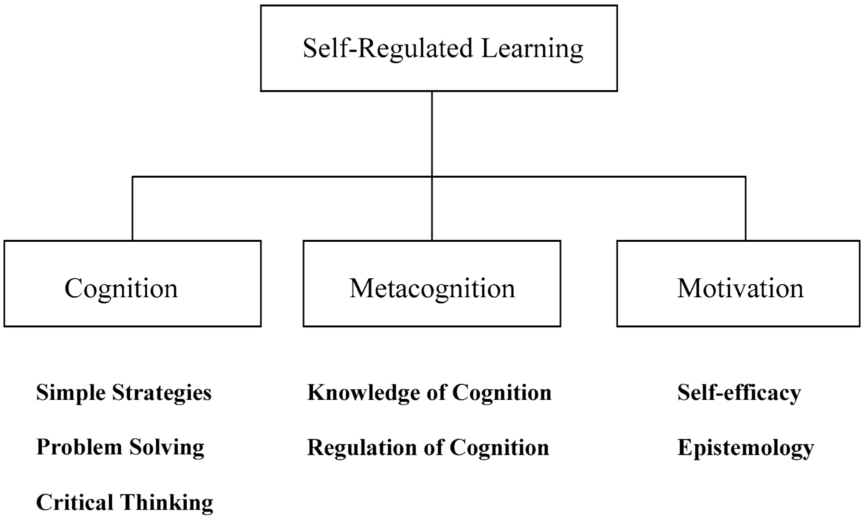

Figure 1: Components of self-regulation learning.

2002; Kahle & Boone, 2000). A second example is the use of active learning strategies such as constructing graphs and tables (House, 2002). A third strategy is to use cloze assessment tasks such as the Koch–Eckstein technique to promote deeper understanding (Koch, 2001). Previous research indicates that self-regulated learners of all ages use a variety of cognitive learning strategies in a flexible way (Pressley & Wharton-McDonald, 1997).

Problem solving strategies are more complex in nature than cognitive strategies. Problem solving strategy instruction usually focuses on either the development of a general problem solving strategy or situated practice using that strategy. One example is the predict–observe–explain (POE) technique studied by Rickey and Stacy (2000). Recent studies report that general problem solving can be broken down into smaller individual steps that are teachable and improve learning (Dhillon, 1998; Peterson & Treagust, 1998). Explicit problem solving instruction helps students to develop deeper levels of understanding compared to students who do not receive problem solving training (Huffman, 1997).

Critical thinking involves a variety of skills such as the individual identifying the source of information, analysing its credibility, reflecting on whether that information is consistent with their prior knowledge, and drawing conclusions based on their critical thinking (Linn, 2000). Research in argumentation (Kuhn, 1999) and critical thinking (Halpern, 1998) indicates that many students fail to utilise sophisticated reasoning even at the college level. Critical thinking can be improved through instruction, although it typically requires an extended instructional sequence (e.g., three months) to do so (Baird & White, 1996; Chang, 1999; Huffman, 1997).

Metacognition

Metacognition as we conceptualise it includes two main subcomponents generally referred to as knowledge of cognition and regulation of cognition (Schraw & Moshman, 1995). Knowledge of cognition refers to what we know about our cognition, and may be considered to include three subcomponents. The first, declarative knowledge, includes knowledge about ourselves as learners and what factors influence our performance. For example, most adult learners know the limitations of their memory system and can plan accordingly. Procedural knowledge, in contrast, refers to knowledge about strategies and other procedures. For instance, most adults possess a basic repertoire of useful strategies such as note-taking, slowing down for important information, skimming unimportant information, using mnemonics, summarising main ideas, and periodic self-testing. Finally, conditional knowledge includes knowledge of why and when to use a particular strategy. Individuals with a high degree of conditional knowledge are better able to assess the demands of a specific learning situation and, in turn, select strategies that are most appropriate for that situation.

Research suggests that an individual's knowledge of cognition is late developing and explicit (Alexander, Carr, & Schwanenflugel, 1995; Baird & White, 1996). Adults tend to have more knowledge about their own cognition and are better able to describe that knowledge than children and adolescents. However, many adults cannot explain their expert knowledge and performance and often fail to spontaneously transfer domain-specific knowledge to a new setting. This suggests that metacognitive knowledge need not be explicit to be useful and, in fact, may be implicit in some situations (Butler & Winne, 1995).

Regulation of cognition typically includes at least three components, planning, monitoring, and evaluation (Schraw & Moshman, 1995). Planning involves the selection of appropriate strategies and the allocation of resources. Planning includes goal setting, activating relevant background knowledge, and budgeting time. Previous research suggests that experts are more self-regulated compared to novices largely due to effective planning, particularly global planning that occurs prior to beginning a task. Monitoring includes the self-testing skills necessary to control learning. Adults monitor at both the local (i.e., an individual test item) and global levels (i.e., all items on a test). Further, even skilled adult learners may be poor monitors under certain conditions (e.g., Pressley & Ghatala, 1990). Evaluation refers to appraising the products and regulatory processes of one's learning. Typical examples include re-evaluating one's goals, revising predictions, and consolidating intellectual gains.

Some researchers and theorists (Butler & Winne, 1995; Pressley, Borkowski, & Schneider, 1989) suggest that self-regulatory processes, including planning, monitoring, and evaluation, may not be conscious or explicit in many learning situations. One reason is that many of these processes are highly automated, at least among adults. A second reason is that some of these processes may develop without any conscious reflection and therefore are difficult to report to others. Also, there is not a readily available language for students and teachers to communicate about such issues. In addition, some science educators believe that science education should reduce the amount of instructional time devoted to conceptual understanding and increase the amount of time devoted to procedural understanding (Duggan & Gott, 2002). The rationale for this claim is that procedural competence in the form of expert problem solving and critical thinking becomes increasingly more important at higher levels of science education.

Motivation

The motivation component shown in Figure 1 includes two important subcomponents, consisting of self-efficacy and epistemological beliefs. Self-efficacy refers to the degree to which an individual is confident that he or she can perform a specific task or accomplish a specific goal (Bandura, 1997). Self-efficacy is extremely important for self-regulated learning because it affects the extent to which learners engage and persist at challenging tasks. Students with higher self-efficacy are more likely to engage in a difficult task and more likely to persist at a task even in the face of initial failures compared to low-efficacy students (Pajares, 1996). Higher levels of self-efficacy are related positively to school achievement and self-esteem. The trends observed with respect to student self-efficacy also generalise to teachers and even schools. Teachers with higher levels of teaching self-efficacy, for example, set higher goals and standards, give more autonomy to students, and help students reach higher levels of achievement than do teachers with lower levels of self-efficacy (Goddard, Hoy, & Hoy, 2000). A number of studies indicate that teacher and student self-efficacy plays an important role in science education (Cannon & Scharmann, 1996; Schoon & Boone, 1998).

Self-efficacy is affected by a number of variables, but especially vicarious learning and modeling. Vicarious learning occurs when individuals learn by observing others perform a skill or discuss a topic. Vicarious learning is advantageous to learners because they are not expected to perform the task, and therefore experience less anxiety, and because they also can focus all of their resources on observing experts. Modeling occurs when learners learn intentionally from other individuals such as teachers and students. Modeling typically includes the teacher breaking a complex task into manageable parts and asking students to demonstrate each part separately in sequence. Bandura (1997) proposed that modeling is effective because it raises expectations that a new strategy can be acquired, in addition to providing a great deal of knowledge about the skill. Peer models are usually the most effective because they are most similar to the learner. Indeed, students are most likely to increase their own self-efficacy when observing a model of similar ability level performing the skill (Schunk, 1996).

There are two main ways to increase students' self-efficacy. One is to use both expert (e.g., teacher) and non-expert (e.g., student peers) models. Modeling can improve cognitive strategies and self-efficacy. The second is to provide as much informational feedback to students as possible. Feedback should indicate not only whether the skill was performed acceptably, but provide as much information as possible about how to improve subsequent performance. Given detailed informational feedback, performance and self-efficacy can increase even after students experience initial difficulty performing a skill.

Epistemological beliefs are those beliefs about the origin and nature of knowledge. Researchers have focused on two aspects of epistemological beliefs in the past decade. One aspect concerns the number of distinct beliefs. Schommer (1994) created a taxonomy of four beliefs she refers to as, (a) quick learning (i.e., something is learned immediately or not at all), (b) innate ability (i.e., learning is constrained by native ability), (c) simple knowledge (i.e., most important ideas are really quite simple), and (d) certain knowledge (i.e., most important ideas do not change over time). Schommer-Aikins (2002) argued that each of these beliefs affects problem solving and critical thinking. Partial support for this claim has been provided by Kardash and Scholes (1996) who found that epistemological beliefs were related positively to critical analysis of a scientific text on the transmission of AIDS. Neber and Schommer-Aikins (2002) also found a relationship between epistemological beliefs and scientific problem solving.

Other researchers have focused on the distinction between different epistemological world views (Hammer & Elby, 2002; Kuhn, 1991). Kuhn and Weinstock (2002) compared absolutists' views (i.e., assertions are facts) to multiplists' views (i.e., assertions are opinions), arguing that multiplists adopt situation world views that promote critical reflection and deeper understanding. In general, there is growing consensus that students and teachers differ with respect to epistemological world views, and that different world views shape instruction and student learning in different ways (Roth & Tobin, 2001; Schraw & Olafson, 2002; Tsai, 2002).

Summary

Self-regulated learning refers to learners' abilities to understand and control their learning environments. Self-regulated learning involves a combination of cognitive strategy use, metacognitive control, and motivational beliefs. Cognitive strategies take the form of simple, problem solving, and critical thinking strategies. Metacognitive processing refers to knowledge and control of cognitive skills, and usually involves planning, monitoring, and evaluating of learning. Finally, the motivational component refers to students' beliefs in their capacity to learn. Motivation takes many forms including self-efficacy and personal epistemological beliefs. Each of these components is necessary, but not sufficient, for skilled science learning. We believe that the role of metacognition is especially important because it enables individuals to monitor their current knowledge and skill levels, plan and allocate limited learning resources with optimal efficiency, and evaluate their current learning state. A number of researchers have argued that cognitive strategies and high motivation alone are insufficient for skilled self-regulation (Butler & Winne, 1995; White & Mitchell, 1994). We believe there are a number of ways that self-regulation can be increased in science classrooms to improve learning. In addition, there are a number of ways to improve metacognition though classroom instruction (Baird & White, 1996; Beeth, 1998; Gunstone & Mitchell, 1998; Mason, 1994). In what follows we describe a variety of ways to increase self-regulation in the science classroom.

Teaching for Metacognition and Self-Regulation in Science Education

Much of the research appearing in science education journals over the past decade has focused on two broad areas; curriculum change in science education and the use of multiple instructional strategies to improve learning (Hurd, 2002; Kelly & Anderson, 2000). This section focuses on six general instructional strategies for improving self-regulation and learning. There is strong consensus among science educators that multiple approaches to learning are necessary to improve overall science achievement (Anderson & Hogan, 2000). These include tested instructional practices, collaborative support involving communities of learners, and the use of technology to enrich the learning environment. Effective science instruction must not only increase learning, but also help students develop the metacognitive life-long learning skills needed to succeed at higher levels of science, and to reconstruct their conceptual knowledge and procedural strategies when necessary. In addition, effective instruction should help students and teachers become aware of the beliefs they hold about science that affect their learning, or in the case of teachers, affect their curricular and pedagogical decisions.

Based on a review of selected science education journals over the past decade we have identified six general areas of instructional strategies for improving science learning. We summarise research in each of the six strategic areas and discuss how these instructional interventions relate to metacognition and self-regulation. These areas are, (a) inquiry based learning, (b) the role of collaborative support, (c) strategy instruction to improve problem solving and critical thinking, (d) strategies for helping students construct mental models and to experience conceptual change, (e) the use of technology, and (f) the impact of student and teacher beliefs. Because of the broad scope of this paper, we do not propose to undertake in-depth reviews of these six areas. Rather, our main goal is to summarise selected research in these areas from a science education perspective and provide recent citations for the reader to pursue in more detail if interested. Each of these six areas have been shown to improve metacognitive awareness and self-regulation.

Inquiry Based Learning

Inquiry based learning and teaching is considered by many as the hallmark of science education. Anderson (2002) distinguished between three types of inquiry. Scientific inquiry is the general process of proposing hypotheses about the world and testing them in a systematic manner. Inquiry learning is the process of students being engaged in learning in which they pose questions and construct solutions; that is, they construct conceptual understanding as the goal of the learning experience (Gunstone & Mitchell, 1998). Inquiry teaching refers to creating a learning environment in which students are able to use a process-oriented approach to pose questions, construct solutions, and test results. Inquiry teaching promotes self-regulation in two ways. One is to stimulate students' active engagement in the learning process by using cognitive learning strategies and metacognitive strategies to monitor their understanding. A second is to help increase motivation to succeed in science by using modeling, but especially modeling active investigation strategies such as predict–observe–explain (POE) (Windschitl, 2002), or question-asking (Chinn & Brown, 2002).

Not all classroom science learning is inquiry based, and not all inquiry based instruction is authentic. Chinn and Malhorta (2002) distinguished between simple inquiry activities and what they refer to as authentic inquiry. Simple and authentic inquiry tasks differ in relation to a variety of important cognitive and epistemological dimensions. For example, authentic inquiry is characterised by generation of research questions, selection of variables, use of experimental controls, being aware of and resisting potential interpretative bias, analysis and interpretation of findings within a coherent theoretical framework, and a detailed account of mechanisms that cause change. Simple inquiry does not meet any of these standards. For example, what Chinn and Malhorta (2002) refer to as simple observation includes research questions provided to students rather than being student generated, lack of experimental control, no protection against bias, construction of simple arguments, and conclusions that do not investigate or validate a coherent theoretical framework.

Authentic inquiry takes years of practice and is not attainable in most science classrooms in the short term (Anderson, 2002; Bell & Linn, 2002; Kuhn, 1989). Nevertheless, it is possible to improve inquiry teaching such that students engage in more than just simple inquiry. Anderson (2002) has summarised key components of inquiry teaching for the teacher and student. Teachers are to facilitate student thinking through scaffolded instruction and explicit reflective thinking. Of special importance is that teachers demonstrate the use of theoretical models in constructing and testing scientific arguments (Kuhn, 1989). Students are expected to take an active role in their learning; to construct hypothesis, and to work collaboratively to test hypotheses and interpret findings. In addition, students should be expected to explain verbally or in writing the problem solving strategies used to solve problems. Doing so promotes self-reflection, an essential component of metacognitive understanding and self-regulation (Baird & White, 1996; Davis, 2003). These aforementioned activities depend upon a number of metacognitive processes described throughout this paper, including planning, monitoring, reflection, and self-evaluation of learning. More explicit instructional interventions are described in the strategies section below.

Chinn and Malhorta (2002) compared differences in epistemologies between authentic and simple inquiry learning environments. Scientists who engage in simple inquiry record what they see. The goal of authentic inquiry is to build and test theoretical models and explain unobservable mechanisms. In contrast, the goal of simple observation is to observe objects in an attempt to describe their behaviour. Authentic inquiry leads to the coordination of theory and data, in which scientists use data to evaluate theory, even in cases where separate sets of data conflict with each other. Thought experiments, in which students consider hypothetical cause–effect relationships, may also play an important role in this process (Gilbert & Reiner, 2000).

Several questions arise when considering inquiry based teaching. The first concerns the mode of implementation of an inquiry based curriculum. There is a general level of agreement that inquiry based learning and teaching should be project based. At least three general inquiry based activities are essential (Chinn & Hmelo-Silver, 2002), including scaffolded experimental design (Khishfe & Fouad, 2002), discussion of results (Halpern, 1998; Kuhn, 1999), and reflection on the process of inquiry (Toth, Suthers, & Lesgold, 2002; Van See, 2000). Some evidence suggests that explicit instruction, especially among younger students, facilitates inquiry oriented experimental design. In addition, there is evidence that students who experience authentic inquiry are more apt to implement similar teaching strategies in their own classrooms (Windschitl, 2002). Authentic inquiry promotes active reflection on problems, as well as construction of explicit conceptual understanding of the problem. Authentic inquiry promotes metacognition and self-regulation because students are better able to monitor their learning and evaluate errors in their thinking or gaps in their conceptual understanding.

A second question concerns the effectiveness of instructional interventions based on inquiry based learning. A recent review of the literature by Anderson (2002) indicates positive, but modest gains in learning for inquiry based instructions. Infusing inquiry into the curriculum may benefit science attitudes and epistemological beliefs, key influences on the motivational aspect of SRL, more than cognitive processes. Inquiry based learning appears to increase the motivation component of self-regulation, perhaps because it leads to a clearer conceptual understanding of the problem. However, some types of cognitive activities such as problem solving may benefit substantially. There appear to be three possible reasons for improved learning from inquiry based instruction. Firstly, inquiry frequently provides communication with some kind of expert who shares strategies and problem solving skills. Secondly, inquiry may increase motivation because the student takes greater ownership and shares authority. Third, inquiry promotes self-reflection, a key component of metacognition (Davis, 2003).

In addition to positive outcomes, several barriers to authentic inquiry instruction have been identified as well. One is the problem of adequate teacher training to use inquiry learning in an effective way (Windschitl, 2002). A second barrier is the lack of agreement among participating teachers or parental reservations to the use of such strategies. The larger goals of inquiry learning (e.g., the generation of research questions) are not currently recognised in large-scale measures of science achievement. Thus, significant quantities of inquiry teaching may have detrimental effects on these traditional measures. A third potential barrier is whether inquiry learning reduces coverage that is seen by many as necessary for progression to higher levels of the science curriculum. These barriers can pose formidable problems for science educators.

Collaboration Among Students and Teachers

Collaboration of all forms is increasingly seen as an essential and important part of education. In the past decade or so, socio-cultural models of learning such as situated learning theory (Lave & Wegner, 1991), cognitive apprenticeships (Collins, Brown, & Newman, 1989), and the work of Vygotsky (1978) have played a prominent role in educational research and practice. In the context of the instructional strategies presented here, collaboration can be viewed as a tool to support approaches that encourage an inquiry orientation, the utilisation of strategies, the development and sharing of mental models, and the making explicit of personal beliefs.

Collaboration in the form of help from teachers and students facilitates learning and SRL for a variety of reasons. Firstly, teacher and student modeling provide explicit examples of how to perform a task and often provide explicit feedback (Schunk, 1996; Webb & Palincsar, 1996). Secondly, collaborative support such as tutors, peer-models, or small groups provide an opportunity for explicit discussion of scientific concepts and reflection that promotes metacognition and self-regulation. For example, explicit discussion promotes planning and evaluation of whether students meet learning goals (Davis, 2003). Students of similar achievement levels may be more effective than teacher–student pairs because the former are able to discuss strategies in the novice's zone of proximal development (Feldman, Campbell, & Lai, 1999). Thirdly, communities of learners have greater knowledge resources than individuals. Finally, social interactions that cut across gender, economic, and ethnic lines promote social equity in the classroom, which enhance motivation and epistemological awareness (Bell & Linn, 2002; Hogan, 1999).

Collaboration in the classroom may occur among students, teachers, and between students and teachers (Hogan, 1999, 2002). Student collaboration usually involves tutors or small collaborative work groups. Research suggests that peer tutors who are judged to be of similar ability to their tutees increase the declarative and procedural knowledge and self-efficacy of those students (Pajares, 1996). Sometimes students are paired with expert mentors in what are referred to as cognitive apprenticeships. These relationships can help novice students develop expertise quickly and provide many opportunities for explicit reflection that builds metacognitive understanding. Research suggests that tutors and cognitive apprenticeship can help novices achieve a higher degree of in-depth learning in a particular domain (Ramaswamy, Harris, & Tschirner, 2001).

One of the most common forms of collaboration are cooperative learning groups. Hogan (1999) developed the Thinking Aloud Together (TAT) program as a means to promote metacognition and self-regulation in a small group collaborative setting. Students in the TAT programs demonstrated greater metacognitive awareness of their learning than students in the control group. Small group collaboration appears to be especially effective when students are engaged in inquiry based discussion of problems (Meyer & Woodruff, 1997) and when students are given explicit training in how to work effectively in small groups (Bianchini, 1997). One potential problem is that student-centred cooperative groups can be difficult to initiate and manage. The *Peer Instruction* program developed at Harvard University by Eric Mazur (`http://galileo.harvard.edu/galileo/lgm/pi/`) is a good example of a successful student collaboration model for large science lecture sections. Guidelines for such groups have also been provided by Webb and Palincsar (1996).

Collaborations among teachers are also important. Two ways to promote collaboration are through cross-level mentoring and co-teaching. Cross-level mentoring refers to an experienced teacher mentoring a less-experienced teacher, usually as part on in-service training (Feldman, Campbell, & Lai, 1999). Training is typically one-on-one or in a small group and focuses on curricular choices and specific pedagogical strategies for improving student learning. In contrast, co-teaching involves two teachers of similar experience teaching in collaboration (Roth, 1998). One advantage to co-teaching is that two teachers are able to make better use of their individual expertise. A second advantage is that one of the teachers can allocate more time to small group work with students while the other teacher direct the ongoing lesson. Co-teaching helps promote the use of cognitive strategies, and better metacognitive monitoring and evaluation, which support higher levels of student self-regulation because teachers have more time to devote to individual students or a small group of students.

Strategy Instruction

Science educators have become increasingly interested in the importance of strategy instruction, which helps students focus their attention more selectively and better integrate information. In addition to being important complements to the instructional suggestions made thus far (inquiry approach and collaboration), strategies serve at least two important functions. One is that they offer the learner a specific procedural routine for solving problems. A second function is that they often present a broad conceptual model for how to solve problems. Linn (2000) proposed four general goals of science education. These include making science accessible, making thinking visible, helping students learn from each other, and promoting lifelong science learning. To accomplish these goals, Linn proposed the *Knowledge Integration Environment* (KIE) framework. At the heart of the KIE framework is the notion that learners use support skills to integrate multiple sources of information into a unified knowledge framework. Strategy instruction is an integral way to accomplish the four goals described by Linn.

Earlier, we identified three levels of strategy instruction. Cognitive strategies focus on the skilled use of a single learning tactic, problem solving strategies that integrate several strategies into a unified plan for categorising and solving problems, and critical thinking strategies that involve gathering, analysing, evaluating, and integrating information for the purpose of drawing a conclusion. We view these three types of strategies as embedded in three levels of instruction. Cognitive strategies are necessary for learning to occur. Problem solving strategies are more sophisticated and are necessary for developing deeper understanding. Critical thinking strategies are still more advanced and are essential for the highest levels of skilled reasoning and decision-making. Critical thinking skills also may be essential to promote metacognitive understanding (Kuhn, 1999). Cognitive strategies enable students to enact individual strategies effectively. In contrast, problem solving and critical thinking strategies enable students to regulate their learning through metacognitive skills such as constructing multiple solutions, testing solutions, and evaluating their answers. In what follows, we summarise and compare these three types of strategies.

Cognitive strategies. There are a wide variety of cognitive strategies that are taught in science classrooms. One general strategy is to use analogies to help students link familiar and unfamiliar concepts (Chinn & Brewer, 1993). A number of studies have examined the effect of drawing an analogy between the human circulatory system and the plumbing in a house (Chinn & Malhorta, 2002). In general, using analogies to map unfamiliar concepts onto familiar schemata in memory has a strong positive effect on learning (Baker & Lawson, 2001; Beeth, 1998; Harrison & Treagust, 1996; Peterson & Treagust, 1998; White & Mitchell, 1994). A second example of strategy instruction is the use of prompted reflection through the use of questions (Blank, 2000; Chinn & Brown, 2002; Osman & Hannafin, 2001). King (1994) reported that student generated questions before or during reading prompted deeper understanding due to selective attention to important main ideas. Scripted problem solving, in which students review the individual steps in problem solving, checking whether each step has been met, also deepens understanding. Davis (2003) found that elementary school students benefited from general reflection prompts that facilitated metacognitive monitoring. Prompted students worked more effectively with other students and constructed more coherent understandings of targeted concepts.

A number of authors have discussed the importance of teaching sets of learning strategies to improve understanding. The effective use of these strategies, at least until they become automated, requires metacognition. Comprehensive reviews by Hattie, Biggs, and Purdie (1996) and Rosenshine, Meister, and Chapman (1996) indicate that strategy instruction typically is moderately to highly successful. Strategy instruction appears to be most helpful for younger and under-achieving students and is most effective when it combines several interrelated strategies. Based on their analysis, Hattie et al. (1996) suggested the following set of general cognitive strategies: self-checking, creating a good study environment, planning and goal setting, reviewing, summarising, and seeking teacher and peer assistance. Dole, Duffy, Roehler, and Pearson (1991) recommended a similar set of five core learning strategies that includes determining what is important to learn, summarising, drawing inferences, generating questions before and during studying, and monitoring one's comprehension. A number of science educators have proposed core sets of strategies to improve content learning (Brooks & Crippen, 2001; Kahle & Boone,

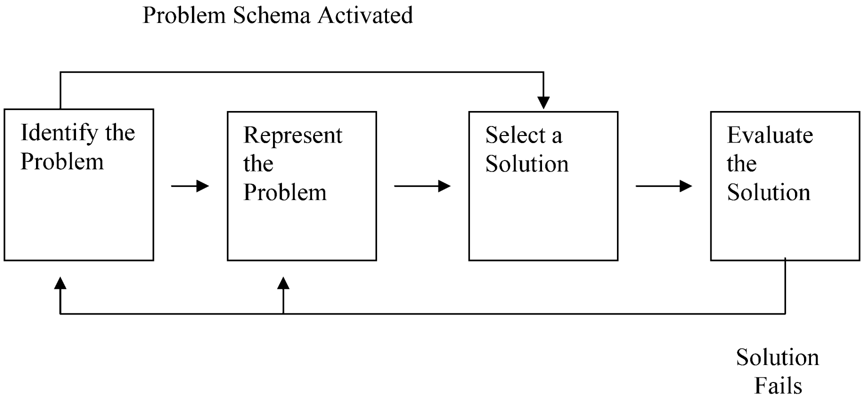

Figure 2: The problem solving process.

2000) and metacognitive awareness (Beeth, 1997; Koch, 2001). Baird and White (1996) proposed four components as part of their *Project for Enhancing Effective Learning* (PEEL), including increasing time to learn, opportunities to learn, teacher guidance, and student support. Part of teacher guidance is to demonstrate cognitive strategies and metacognitive problem solving. Student support offers a collaborative framework for purposeful inquiry.

Problem solving. Effective problem solving depends on two key components: expert knowledge that supports metacognition and problem solving skills (Gunstone, 1999b). Developing expertise takes years, although students can develop surprising amounts of expertise quickly through systematic instruction, scaffolded laboratory experiences, and peer support (Ericsson, 1996). Using a systematic problem solving strategy/algorithm is also important. Figure 2 shows one such strategy, which involves identifying the problem, representing the problem, selecting an appropriate solution strategy, and evaluating the solution. Figure 2 also shows several important feedback loops. One loop occurs when experts possess schematic knowledge that enables them to bypass a detailed search for solution strategies. Two other feedback loops occur when solutions fail and individuals must return to a new problem representation or solution strategy.

Research suggests that students benefit greatly from problem solving instruction. Teaching a general strategy such as that shown in Figure 2 is less effective than instruction geared toward solving representative problems in a specific situation. For example, Chang (1999) found that training in solving earth science problems over a six week period improved problem solving, but also especially improved transfer. Dhillon (1998) found that instruction and modeling of the representation phase of problem solving was especially helpful.

Research suggests that there are at least three general instructional principles for improving problem solving (Chang, 1999; Huffman, 1997). One is to facilitate the acquisition of expert knowledge, which, in itself, requires a set of strategies and an appropriate view of knowledge. To do so, students must usually acquire as much expert knowledge as efficiently as possible through some combination of organised instruction from an expert, as well as reflective practice under the guidance of a teacher or peer. A second principle is to develop an explicit awareness of a problem solving strategy such as that in Figure 2 that is appropriate for the types of problems being solved. One way to do so is for the instructor to model his or her preferred problem solving methods explicitly. A third is to use external representations whenever possible to reduce unnecessary cognitive load. These representations can take the form of summary tables, flowcharts, causal diagrams, timelines, etc. Of central importance is that the learner reduces the amount on information held in memory by translating it onto paper or into a physical model (Gunstone & Mitchell, 1998; Perkins, 1993). These problem solving strategies have been found to improve metacognition and self-regulation because that enable the student to reallocate limited resources and solve problems more efficiently (Butler & Winne, 1995; Kahle & Boone, 2000).

Critical thinking. Developing a repertoire of critical thinking skills for the science classroom is a challenging task. Halpern (1998) and Kuhn (1999) have written extensively about improving critical thinking skills. A core set of skills, which consist of identifying relevant information, constructing arguments, testing the credibility of information and hypotheses, and forming plausible conclusions is generally agreed on (Bruning et al., 2003; Kuhn, 1991; Vosniadou, 1994). It is especially important to help students develop better metacognitive monitoring through explicit reflection and monitoring training in relation to the use of such critical thinking skills. For example, Delclos and Harrington (1991) examined fifth and sixth-grader's ability to solve computer problems after assignment to one of three conditions. The first group received specific problem solving training, the second received problem solving plus self-monitoring training and practice, while the third received no training. The problem solving and monitoring group solved more of the difficult problems than either of the remaining groups and also took less time to do so.

More recently, Blank (2000) proposed a model of critical thinking in science called the *metacognitive learning cycle* (MLC). The MLC emphasises the systematic use of discussions and reflection to promote explicit metacognitive understanding of critical thinking and problem solving. The MLC consists of four interrelated steps, which include concept introduction, concept application, concept assessment, and concept exploration. Students are asked to reflect upon their progress at each step either individually or in small groups. In comparison with groups that did not use explicit reflection, the MLC experienced greater conceptual restructuring and understanding of course content.

As previously suggested, many science educators believe that reflection is the most important cognitive mechanism for promoting critical thinking and metacognition (Davis, 2003; Gunstone, 1999a; Zembal-Saul, Blumenfeld, & Krajcik, 2000). Nichols, Tippins, and Wieseman (1997) provided a comprehensive review of reflection and the role that critical reflection plays in critical thinking and self-regulation.

Critical reflection emphasises the use of alternative perspectives and uses of knowledge and thinking. As noted in the prior section, collaboration plays a key role in providing these alternative perspectives. In addition, Nichols et al. (1997) identified a number of learning tools that promote critical reflection and metacognition in the classroom, including portfolios, journals, and examination of cases.

The Development of Mental Models and Conceptual Change

One area of profound importance to science education and a key component of authentic inquiry, is understanding how to help students and teachers construct mental models of scientific phenomena and the role that metacognition plays in this process (Beeth, 1998; Gunstone & Mitchell, 1998). Hogan and Thomas (2001) argue that mental models are necessary to think metacognitively about complex systems. Students have difficulty reflecting on complex phenomena without mental models, and as a consequence, find it difficult to monitor and self-regulate their own learning.

Hogan and Thomas (2001) summarised a number of differences between experts and novices when constructing mental models of a scientific phenomenon. Four components of the model-construction process were of special importance, including model construction, model quantification, model interpretation, and model revision. In general, experts who construct mental models focus on the dynamic interrelationships within the model, whereas novices focus to a greater extent on isolated component variables. These differences may be due to experience and access to skilled mentors, but also to differences in what Hogan and Thomas refer to as a modeling epistemology (i.e., the beliefs people have about the utility and credibility of models). Unfortunately, research suggests that many science teachers do not possess strong skills related to the use of mental models (Beeth, 1997; Kuhn, 1989; Van Driel & Verloop, 1999). However, technology may play an important role as the medium for abstracting external representations of mental models that would supply teachers with data upon which to provide instructional feedback.

Understanding and constructing mental models is an essential component of science achievement. However, it is possible that a student may construct an inappropriate mental model that misrepresents important relationships and leads to inaccurate conclusions. In such cases, teachers are faced with the dilemma of conceptual change; that is, how to change a student's or fellow teacher's internal representation of a domain or phenomenon. Much has been written on conceptual change since the pioneering work of Posner, Strike, Hewson, and Gertzog (1982). Conceptual change is not possible without some degree of intellectual conflict, although that is sharp disagreement as to how much conflict is optimal. Most recent models of conceptual change span a continuum from weak to radical conceptual change (Chinn & Brewer, 1993; Chinn & Malhorta, 2002). The dilemma that science teachers face is whether to help students restructure their knowledge through either weak or radical conceptual change processes (Pintrich, Marx, & Boyle, 1993). Experts agree that some degree of cognitive disequilibrium is necessary, although it is unclear how much and under what circumstances (Chinn & Brewer, 1993; Gunstone & Mitchell, 1998; Pintrich et al., 1993). Greater levels of cognitive disequilibrium appear to facilitate conceptual change, although there are important differences across younger and older students. One of the most common approaches is to ask students to model anomalous data (Niaz, 2001; Nieswandt, 2001; Novak, 2002; Shepardson, 1999). Constructing mental models based on data in the context of hands-on or laboratory instruction is especially helpful because it promotes strategy use, reflection, and evaluation (Weaver, 1998).

Genuine conceptual change involves at least three distinct stages, including revealing student preconceptions, creating conceptual conflict, and encouraging cognitive accommodation. Research suggests that teacher directed discussions and collaborative work among students are useful ways to reveal student preconceptions. Another strategy is the use of metaphors to reveal naïve preconceptions (Tobin & Tippins, 1996; Thomas & McRobbie, 1999, 2001; Vosniadou, 1994). Yet a third strategy is to induce the need for conceptual change through failed experiments (Tabachnick & Zeichner, 1999). These strategies are important because they promote explicit metacognitive awareness that enables students to self-regulate their learning in cooperative groups (Hogan, 1999) and individually (Beeth, 1998; Gunstone & Mitchell, 1998).

The Use of Technology

Technology has the potential to support self-regulated learning in science education in a number of ways. Typically, this involves supporting the other instructional strategies. For example, using hardware and software (both digital computer and other) in the process of inquiry, as a construction tool for creating representations of mental models, as a collaborative communication medium, to model expert techniques and to provide feedback during problem solving. In this capacity, technology supports self-regulation by functioning as: a knowledge representation tool, a cognitive scaffold, a feedback engine, and a collaborative communication device.

The development and use of cognitive strategies like creating multiple external representations can be facilitated successfully with technology (Jonassen, Carr, & Yueh, 1998). Students can use semantic networking software (e.g., Inspiration™) to represent their understanding of complex phenomenon before, during, and after instruction. These two dimensional representations illustrate the important relationships between concepts (structural knowledge) and can serve to help students explicitly model their thinking in a medium that can be updated as student's understanding evolves. In addition, technology can be used to promote metacognitive activities such planning and monitoring (Puntambekar, 1995). Puntambekar and duBoulay (1997) developed a computer assisted instructional system called *Metacognition in Studying from Texts* (MIST) to train students to reflect upon what they were reading and to monitor their understanding.

Technology can be implemented as a cognitive scaffold for novice science problem solvers. As such, 'just-in-time' examples of expert problem solving strategies and individualised performance-related feedback can be generated and delivered. Engaging students in studying expert strategies in the form of worked examples improves novice student problem solving and metacognition (Atkinson et al., 2000). These examples can be generated dynamically as students are working through materials, or simply be delivered on demand. This can be viewed as a proxy for teacher modeling as an instructional strategy.

Electronic assessment systems that provide students with instantaneous knowledge of results and performance related feedback are effective for improving performance in science courses (Dufresne et al., 2002; Penn, Nedeff, & Gozdzik, 2000). These systems can serve a metacognitive function for students who use them as the feedback provided can be individualised based upon student response patterns and can include suggestions which make students cognition explicit (Butler & Winne, 1995). Instructional design in such systems is a serious consideration in terms of the limited capacity of working memory and its implications for student performance (Brooks & Crippen, 2001).

Solving analytical problems with data analysis, visualisation and organisation tools such as spreadsheets and dynagrams (dynamic diagrams), allows students to focus on larger problem solving issues while offloading certain necessary information (relationships, procedures and data) to the machine. In this way, students are better able to focus their cognitive resources on monitoring and evaluating the quality of solution produced (Pea, 1993a). An example of such a tool is the 2-D Optic Dynagram simulator that was developed to serve as a symbolic representation of optical scenarios that were used to test questions related to light and lenses (Pea, 1993b).

Having science students use technology to create both static and dynamic models is thought to broaden and strengthen their mental models and support critical thinking (Stratford, 1997). Integrating the functional and causal relationships of a complex dynamic system like global climate, electron transport, or plate tectonics requires the production of a quality mental model (Greca & Moreira, 2000). Dynamic computer modeling software allows students to create functional analytical models. These models can be built as either representations of mental models or representations of observable physical phenomena. Variables within these models can be manipulated and temporal patterns can be analysed against hypothesised predictions. Just as semantic representations of student thinking can be updated to better represent their current understanding, dynamic models of physical phenomena can continuously be enhanced as the phenomenon evolves, or is better understood. Constructing models using computers should enable students to metacognitively evaluate their learning.

Finally, electronic communication and collaboration tools like e-mail, chat, and threaded discussion support self-regulation in a number of ways. One notable collaboration tool is the Computer Supported Intentional Learning Environment (CSILE) developed to support student inquiry (Scardamalia & Bereiter, 1996). CSILE (now Knowledge Forum) provides students and teachers with a shared space that is used to organise course concepts and student ideas. Student contributions are scaffolded in the sense that they are prompted to post notes that use language to support knowledge building.

Student and Teacher Beliefs

Beliefs play a crucial role in science learning for both students and teachers (McRobbie & Thomas, 2000; Roth & Tobin, 2001). Self-efficacy and epistemological beliefs appear to be of particular importance. Self-efficacy refers to the degree that individuals feel capable of accomplishing a particular task or goal (Bandura, 1997). Higher levels of self-efficacy correspond to greater engagement in a difficult task and higher levels of persistence when faced with setbacks. Self-efficacy is important because students generally lose confidence and interest in science with age (Pell & Jarvis, 2001). Effective instruction, peer modeling, and cooperative learning communities all appear to improve student self-efficacy (Pajares, 1996). Detailed informational feedback increases student self-efficacy as well, but especially self-regulatory skills and metacognition (Butler & Winne, 1995; White, 1998).

A number of factors appear to affect pre-service teachers' self-efficacy beliefs. One is that simple beliefs about science phenomena, such as the structure of the solar system, are related to lower teacher self-efficacy (Schoon & Boone, 1998). Low self-efficacy teachers also had fewer alternative conceptions of relevant subject matter than high self-efficacy teachers. Access to high quality instruction increases pre-service teachers' self-efficacy (Ramey-Gassert, Shroyer, & Staver, 1998). In addition, cooperative field experiences increase self-efficacy, especially when low self-efficacy teachers participate with high self-efficacy teachers (Cannon & Scharmann, 1996). For practicing teachers, support from fellow teachers and administrators is an important determinant of self-efficacy. Continuing education also predicts self-efficacy, although it is still unknown whether continuing education causes self-efficacy or the reverse.

Epistemological beliefs refer to individuals' beliefs about the origin and nature of knowledge (Reiner & Gilbert, 2000). Researchers have distinguished between realist versus relativist epistemological world views (Elby & Hammer, 2001; Hammer & Elby, 2002). Realism corresponds to the belief that knowledge is relatively simple, fixed, and teachable in the same way to a wide array of students. Relativism corresponds to the belief that knowledge is messy, changing, and must be personalised through experience.

Students holding realist world views characterised by unsophisticated epistemological beliefs typically achieve less than students with relativist world views, even when other variables are held constant (Hofer & Pintrich, 1997; King & Kitchener, 1994; Schommer-Aikins, 2002). Jehng, Johnson, and Anderson (1993) found that epistemological beliefs differ across academic disciplines among college undergraduate and graduate students. Students in disciplines, such as the humanities, were more likely to believe that knowledge is uncertain than students in disciplines, such as physics. Compared with undergraduates, graduate students were more likely to believe that knowledge is uncertain and develops incrementally (they did not believe in quick learning). Bendixen, Schraw, and Dunkle (1998) found that epistemological beliefs were related to moral reasoning among adults. Individuals adopting beliefs in complex, incremental knowledge reasoned at a higher level on the Defining Issues Test. Kardash and Scholes (1996) reported that beliefs in certain knowledge were associated with lower scores on the Need for Cognition Scale and in written measures of cognitive reasoning. Collectively, these findings suggest that students with more sophisticated epistemological beliefs are more likely to reflect on problems and reach more sophisticated conclusions.

Kuhn and colleagues (Kuhn, 1991; Kuhn, Cheney, & Weinstock, 2000) found that epistemological beliefs are related to one's ability to argue persuasively and to use metacognitive skills and knowledge to self-regulate one's learning. In these studies, individuals were classified as an absolutist (one who believes that knowledge is absolutely right or wrong), a multiplist (one who believes that knowledge is completely relative), or an evaluative theorist (one who believes that knowledge, though relative, is constrained by situational factors such as commonly accepted rules) on the basis of their beliefs about the certainty of knowledge. Evaluative theorists were more likely than absolutists to provide legitimate evidence in support of an argument. In addition, compared with absolutists, evaluative theorists generated a greater number of plausible alternative theories and provided better counterarguments.

Teachers' epistemological beliefs affect their curricular and pedagogical decisions (Reybold, 2001; Roth & Tobin, 2001; Schraw & Olafson, 2002; White, 2000). For example, teachers who endorse realist beliefs are more likely to rely on textbooks and standardised curriculum, use conventional text, minimise field experiences, and limit the role of hypothesis testing and thought experiments (Bell & Linn, 2002; Elby & Hammer, 2001; Hogan, 2000; Neber & Schommer-Aikins, 2002; Reiner & Gilbert, 2000; Tsai, 2001).

Teachers with unsophisticated epistemological beliefs conduct less challenging classrooms. One problem with the classrooms of such teachers is that they convey and promote images of science as static and/or beyond the reach of all but the most capable students (Bell & Linn, 2002). Realist teachers also spend more time engaged in direct instruction and set work and less time in critical inquiry, which many have argued is the cornerstone of scientific investigation. Moreover, realist teachers may be less able or unwilling to model skilled argumentation in their classrooms (Kuhn, 1999). In contrast, teachers characterised by sophisticated epistemological beliefs promote inquiry and argumentation, using specific strategies such as debate, generating and critiquing arguments, group based projects that facilitate synthesis of ideas (Bell & Linn, 2002; Roth, McRobbie, Lucas, & Boutonne, 1997). Research indicates that expert science teachers may promote sophisticated reasoning and argumentation skills through co-teaching (Roth, Tobin, & Zimmermann, 2002).

Overall, self-efficacy and epistemological beliefs help to motivate students and teachers motivation (Elby & Hammer, 2001; Neber & Schommer-Aikins, 2002). Students who are more self-efficacious are better self-regulators, in part, due to better use of metacognitive skills and knowledge (Baird & White, 1996; Blank, 2000). Modeling helps students increase their self-efficacy (Pajares, 1996) and metacognitive skills (Kuhn, 1999). Strategy instruction also improves self-efficacy (Pressley et al., 1989), self-regulated learning (Butler & Winne, 1995), and metacognitive awareness (Alexander et al., 1995; Schraw & Moshman, 1995).

Summary and Conclusions

Self-regulated learning theory evolved from Bandura's (1997) social-cognitive learning theory. Contemporary self-regulated learning theory focuses on the transition from dependent to autonomous learner. Several main themes emerge from this research. The first is that self-regulated learners rely on an integrated repertoire of cognitive, metacognitive, and motivational skills. Second, self-regulated learners use these skills to plan, set goals, implement and monitor strategy use, and evaluate their learning goals. Third, self-regulated learners use a wide variety of strategies in flexible ways, augmenting these strategies with a variety of adaptive motivational beliefs such as high self-efficacy and epistemological world views.

This review summarised six general instructional strategies that promote self-regulation by helping students develop a repertoire of cognitive skills, metacognitive awareness, and resilient motivational beliefs. There are many ways that cognitive, metacognitive, and motivational skills are enhanced using these strategies. Table 1 summarises a few of the main ways that each of the six instructional strategies improves cognition, metacognition and motivation.

Our review of the science education literature reveals that while there has been some research focused on metacognition little is available on the broader topic of self-regulation. We argue that self-regulation is of tremendous importance to all learners and the general education literature supports this view. Schools need to prepare students as life-long learners in science and other academic domains as well. We feel that there is a great deal that science educators currently do, and could do in the future, to promote self-regulation and that past research on metacognition provides something of a platform for moving forward in promoting and researching self-regulated learning. Research suggests that when these instructional strategies are implemented, science learning and achievement improves. We hope our review prompts science educators and researchers to think more carefully about the infusion of instructional strategies that do so.

Correspondence: G. Schraw, University of Nevada, Las Vegas, 4505 Maryland Parkway, Box 453003, Las Vegas, NV 89154-3003, USA

References

Alexander, J. M., Carr, M., & Schwanenflugel, P. J. (1995). Development of metacognition in gifted children: Directions for future research. *Developmental Review, 15*(1), 1–37.

Table 1
Ways the Six Instructional Strategies Increase Cognitive, Metacognitive, and Motivational Processes.

	Cognitive processes	Metacognitive processes	Motivational processes
Inquiry	Promotes critical thinking through experimentation and reflection	Improves explicit planning, monitoring, and evaluation	Provides expert modeling
Collaboration	Models strategies for novices	Models self reflection	Provides social support from peers
Strategies	Provides a variety of strategies	Helps students develop conditional knowledge	Increases self-efficacy to learn
Mental Models	Provides explicit model to analyse	Promotes explicit reflection and evaluation of the proposed model	Promotes radical restructuring and conceptual change
Technology	Illustrates skills with feedback. Provides models and simulates data	Helps students test, evaluate, and revise models	Provides informational resources and collaborative support
Personal Beliefs	Increases engagement and persistence among students	Promotes conceptual change and reflection	Promotes modeling epistemology characteristic of expert scientists

Anderson, R. D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education, 13*(1), 1–12.

Anderson, C. W., & Hogan, K. (2000). Preface: Designing programs for science learning. *Journal of Research in Science Teaching, 37*(7), 627–628.

Atkinson, R. K., Derry, S. J., Renkl, A., & Wortham, D. (2000). Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research, 70*(2), 181–214.

Baird, J. R., & White, R. T. (1996). Metacognitive strategies in the classroom. In D. F. Treagust, R. Duit, & B. J. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 190–200). New York: Teachers College Press.

Baker, W. P., & Lawson, A. E. (2001). Complex instructional analogies and theoretical concept acquisition in college genetics. *Science Education, 85*(6), 665–683.

Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York: Freeman.

Beeth, M. E. (1997). Teaching for conceptual change: Using status as a metacognitive toolkit. *Science Education, 82*(1), 343–356.

Beeth, M. E. (1998). Facilitating conceptual change learning: The need for teachers to support metacognition. *Journal of Science Teacher Education, 9*(1), 49–61.

Bell, P., & Linn, M. C. (2002). Beliefs about science: How does science instruction contribute? In B. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 321–346). Mahwah, NJ: Erlbaum.

Bendixen, L. D., Schraw, G., & Dunkle, M. E. (1998). Epistemic beliefs and moral reasoning. *The Journal of Psychology, 13*(3), 187–200.

Bianchini, J. A. (1997). Where knowledge construction, equity, and context intersect: Student learning of science in small groups. *Journal of Research in Science Teaching, 34*(10), 1039–1065.

Blank, L. M. (2000). A metacognitive learning cycle: A better warranty for student understanding. *Science Education, 84*(4), 486–506.

Brooks, D. W., & Crippen, K. J. (2001). Learning difficult content using the web: Strategies make a difference. *Journal of Science Education and Technology, 10*(4), 283–285.

Bruning, R. H., Schraw, G. J., Norby, M. M., & Ronning, R. R. (2003). *Cognitive psychology and instruction* (4th ed.). Columbus, OH: Prentice-Hall.

Butler, D. L., & Winne, P. H. (1995). Feedback and self-regulated learning: A theoretical synthesis. *Review of Educational Research, 65*(3), 245–281.

Cannon, J. R., & Scharmann, L. C. (1996). Influence of cooperative early field experience on preservice elementary teachers' science self-efficacy. *Science Education, 80*(4), 419–436.

Chang, C. (1999). The use of problem-solving based instructional model in initiating change in students' achievement and alternative frameworks. *International Journal of Science Education, 21*(4), 373–388.

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*(1), 1–49.

Chinn, C., & Brown, D. A. (2002). Student-generated questions: A meaningful aspect of learning in science. *International Journal of Science Education, 24*(5), 521–549.

Chinn, C. A., & Hmelo-Silver, C. E. (2002). Authentic inquiry: Introduction to the special section. *Science Education, 86*(1), 171–174.

Chinn, C. A., & Malhorta, B. A. (2002). Epistemologically authentic inquiry in the schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*(2), 175–218.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453–494). Hillsdale, NJ: Erlbaum.

Davis, E. A. (2003). Prompting middle school science students for productive reflection: Generic and directed prompts. *The Journal of the Learning Sciences, 12*(1), 91–142.

Delclos, V. R., & Harrington, C. (1991). Effects of strategy monitoring and proactive instruction on children's problem-solving performance. *Journal of Educational Psychology, 83*(1), 35–42.

Dhillon, A. S. (1998). Individual differences with problem-solving strategies used in physics. *Science Education, 82*(3), 379–405.

Dole, J. A., Duffy, G. G., Roehler, L. R., & Pearson, P. D. (1991). Moving from the old to the new: Research on reading comprehension instruction. *Review of Educational Research, 61*(3), 239–264.

Dufresne, R., Mestre, J., Hart, D. M., & Rath, K. A. (2002). The effect of Web-based homework on test performance in large enrollment introductory physics courses. *Journal of Computers in Mathematics and Science Teaching, 21*(3), 229–251.

Duggan, S., & Gott, R. (2002). What sort of science education do we really need? *International Journal of Science Education, 24*(7), 661–679.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education, 85*(5), 554–567.

Ericsson, K. A. (1996). The acquisition of expert performance. In K. A. Ericsson (Ed.), *The road to excellence: The acquisition of expert performance in the arts, sciences, sports, and games* (pp. 1–50). Mahwah, NJ: Erlbaum.

Feldman, A. I., Campbell, R. L., & Lai, M. K. (1999). Improving elementary school science teaching by cross-level mentoring. *Journal of Science Teacher Education, 10*(1), 55–67.

Gilbert, J. K., & Reiner, M. (2000). Thought experiments in science education: Potential and current realization. *International Journal of Science Education, 22*(3), 265–283.

Goddard, R. D., Hoy, W. K., & Hoy, A. W. (2000). Collective teacher efficacy: It's meaning, measure and impact on student achievement. *American Educational Research Journal, 37*(2), 479–508.

Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modeling. *International Journal of Science Education, 22*(1), 1–11.

Gunstone, R. (1999a). Content knowledge, a reflection, and their intertwining: A response to the paper set. *Science Education, 83*(3), 393–396.

Gunstone, R. (1999b). The importance of specific science content in the enhancement of metacognition. In P. J. Fensham, R. F. Gunstone, & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 131–146). London, England: The Falmer Press.

Gunstone, R., & Mitchell, I. J. (1998). Metacognition and conceptual change. In J. L. Mintzes, J. H. Wandersee, & J. D. Noval (Eds.), *Teaching for science education: A human constructivist view* (pp. 133–163). San Diego, CA: Academic Press.

Halpern, D. F. (1998). Teaching critical thinking for transfer across domains. *American Psychologist, 53*(9), 449–455.

Hammer, D., & Elby, A. (2002). On the form of a personal epistemology. In B. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 169–190). Mahwah, NJ: Erlbaum.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*(5), 509–534.

Hattie, J., Biggs, J., & Purdie, N. (1996). Effects of learning skills interventions on student learning: A meta-analysis. *Review of Educational Research, 66*(2), 99–136.

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research, 67*(1), 88–140.

Hogan, K. (1999). Sociocognitive roles in science group discourse. *International Journal of Science Education, 21*(8), 855–882.

Hogan, K. (2000). Exploring a process view of students' knowledge about the nature of science. *Science Education, 84*(1), 51–70.

Hogan, K. (2002). Small groups' ecological reasoning while making an environmental management decision. *Journal of Research in Science Teaching, 39*(4), 341–368.

Hogan, K., & Thomas, D. (2001). Cognitive comparisons of students' systems modeling in ecology. *Journal of Science Education and Technology, 10*(4), 319–345.

House, D. J. (2002). The motivational effects of specific teaching activities and computer use for science learning: Findings from the third international mathematics and science study (TIMSS). *International Journal of Instructional Media, 29*(4), 423–440.

Huffman, D. (1997). Effect of explicit problem solving instruction on high school students' problem-solving performance and conceptual understanding of physics. *Journal of Research in Science Teaching, 34*(6), 551–570.

Hurd, P. D. (2002). Modernizing science education. *Journal of Research in Science Teaching, 39*(1), 3–9.

Jehng, J. J., Johnson, S. D., & Anderson, R. C. (1993). Schooling and student's epistemological beliefs about learning. *Contemporary Educational Psychology, 18*(1), 23–35.

Jonassen, D. H., Carr, C., & Yueh, H. P. (1998). Computers as mind tools for engaging learners in critical thinking. *TechTrends, 43*(2), 24–32.

Kahle, J. B., & Boone, W. (2000). Strategies to improve student science learning: Implications for science teacher education. *Journal of Science Teacher Education, 11*(2), 93–107.

Kardash, C. M., & Scholes, R. J. (1996). Effects of preexisting beliefs, epistemological beliefs, and need for cognition on interpretation of controversial issues. *Journal of Educational Psychology, 88*(2), 260–271.

Kelly, G. J., & Anderson, C. W. (2000). Learning with understanding. *Journal of Research in Science Teaching, 37*(8), 757–759.

Khishfe, R., & Fouad, A. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

King, P. M., & Kitchener, K. S. (1994). *Developing reflective judgment*. San Francisco: Jossey-Bass.

King, A. (1994). Guiding knowledge construction in the classroom: Effects of teaching children how to question and how to explain. *American Educational Research Journal, 31*(2), 338–368.

Koch, A. (2001). Training in metacognition and comprehension of physics texts. *Science Education, 85*(6), 758–768.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*(4), 674–689.

Kuhn, D. (1991). *The skills of argument*. Cambridge: Cambridge University Press.

Kuhn, D. (1999). A developmental model of critical thinking. *Educational Researcher, 28*(1), 16–26.

Kuhn, D., & Weinstock, M. (2002). What is epistemological thinking and why does it matter? In B. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 103–177). Mahwah, NJ: Erlbaum.

Kuhn, D., Cheney, R., & Weinstock, M. (2000). The developmental of epistemological understanding. *Cognitive Development, 15*(3), 309–328.

Lave, J., & Wegner, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.

Linn, M. C. (2000). Designing the knowledge integration environment. *International Journal of Science Education, 22*(8), 781–796.

Mason, L. (1994). Cognitive and metacognitive aspects in conceptual change by analogy. *Instructional Science, 22*(2), 157–187.

McRobbie, C. J., & Thomas, G. P. (2000). Changing the learning environment to enhance explaining and understanding in a year 12 chemistry classroom. *Learning Environments Research, 3*(3), 209–227.

Meyer, K., & Woodruff, E. (1997). Consensually driven explanation in science teaching. *Science Education, 81*(2), 173–192.

Neber, H., & Schommer-Aikins, M. (2002). Self-regulated science learning with highly gifted students: The role of cognitive, motivational, epistemological, and environmental variables. *High Ability Studies, 13*(1), 59–74.

Niaz, M. (2001). Response to contradiction: Conflict resolution strategies used by students in problem solving of chemical equilibrium. *Journal of Science Education and Technology, 10*(2), 205–211.

Nichols, S. E., Tippins, D., & Wieseman, K. (1997). A toolkit for developing critically reflective science teachers. *Research in Science Education, 27*(2), 175–194.

Nieswandt, M. (2001). Problems and possibilities for learning in an introductory chemistry course from a conceptual change perspective. *Science Education, 85*(2), 158–179.

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate prepositional hierarchies leading to the empowerment of learners. *Science Education, 86*(4), 548–571.

Osman, M. E., & Hannafin, M. J. (2001). Effects of advance questioning and prior knowledge on science learning. *Journal of Educational Research, 52*(1), 5–13.

Pajares, F. (1996). Self-efficacy beliefs in academic settings. *Review of Educational Research, 66*(4), 543–578.

Pea, R. D. (1993a). Practices of distributed intelligence and designs for education. In G. Salomon (Ed.), *Distributed cognitions: Psychological and educational considerations* (pp. 47–87). New York: Cambridge University Press.

Pea, R. D. (1993b). Learning scientific concepts through material and social activities: Conversational analysis meets conceptual change. *Educational Psychologist, 28*(3), 265–277.

Pell, T., & Jarvis, T. (2001). Developing attitude to science scales for use with children of ages five to eleven years. *International Journal of Science Education, 23*(8), 847–862.

Penn, J. H., Nedeff, V. M., & Gozdzik, G. (2000). Organic chemistry and the Internet: A web-based approach to homework and testing using the WE_LEARN system. *Journal of Chemical Education, 77*(2), 227–231.

Perkins, D. N. (1993). Person-plus: A distributed view of thinking and learning. In G. Salomon (Ed.), *Distributed cognitions: Psychological and educational considerations* (pp. 88–110). New York: Cambridge University Press.

Peterson, R. F., & Treagust, D. F. (1998). Learning to teach primary science through problem-based learning. *Science Education, 82*(2), 215–237.

Pintrich, P. (2000). The role of goal orientation in self-regulated learning. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 452–501). San Diego, CA: Academic Press.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual in the process of conceptual change. *Review of Educational Research, 63*(1), 167–199.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227.

Pressley, M., Borkowski, J., & Schneider, W. (1989). Good information processing: What is it and what education can do to promote it. *Journal of Experimental Child Psychology, 43*(2), 194–211.

Pressley, M., & Ghatala, E. S. (1990). Self-regulated learning: Monitoring learning from text. *Educational Psychologist, 25*(1), 19–33.

Pressley, M., & Wharton-McDonald, R. (1997). Skilled comprehension and its development through instruction. *School Psychology Review, 26*(4), 448–466.

Puntambekar, S. (1995). Helping students learn ‘how to learn’ from texts: Towards and ITS for developing metacognition. *Instructional Science, 23*(1–3), 163–182.

Puntambekar, S., & duBoulay, B. (1997). Design and development of MIST: A system to help students develop metacognition. *Journal of Educational Computing Research, 16*(1), 1–35.

Ramaswamy, S., Harris, I., & Tschirner, U. (2001). Student peer teaching: An innovative approach to instruction in science and engineering education. *Journal of Science Education and Technology, 10*(2), 165–171.

Ramey-Gassert, L., Shroyer, M. G., & Staver, J. R. (1998). A qualitative study of factors influencing science teaching self-efficacy of elementary level teachers. *Science Education, 80*(3), 283–315.

Reiner, M., & Gilbert, J. (2000). Epistemological resource for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489–505.

Reybold, L. E. (2001). Encouraging the transformation of personal epistemology. *Qualitative Studies in Education, 14*(3), 413–428.

Rickey, D., & Stacy, A. M. (2000). The role of metacognition in learning chemistry. *Journal of Chemical Education, 77*(7), 915–919.

Rosenshine, B., Meister, C., & Chapman, S. (1996). Teaching students to generate questions: A review of the intervention studies. *Review of Educational Research, 66*(2), 181–221.

Roth, W. (1998). Science teaching as knowledgability: A case study of knowing and learning during coteaching. *Science Education, 82*(3), 357–377.

Roth, W., & Tobin, K. (2001). The implications of coteaching/cogenerative dialogue for teacher evaluation: Learning from multiple perspectives of everyday practice. *Journal of Personnel Evaluation in Education, 15*(1), 7–29.

Roth, W., McRobbie, C. J., Lucas, B., & Boutonne, S. (1997). Why may students fail to learn from demonstrations? A social practice perspective on learning in physics. *Journal of Research in Science Teaching, 34*(5), 509–533.

Roth, W., Tobin, K., & Zimmermann, A. (2002). Coteaching/cogenerative dialoguing: Learning environments research as classroom praxis. *Learning Environments Research, 5*(1), 1–18.

Scardamalia, M., & Bereiter, C. (1996). Computer support for knowledge-building communities. In T. Koschmann (Ed.), *CSCL: Theory and practice of an emerging paradigm* (pp. 249–268). Mahwah, NJ: Erlbaum.

Schommer, M. (1994). Synthesizing epistemological belief research: Tentative understandings and provocative confusions. *Educational Psychology Review, 6*(4), 293–320.

Schommer-Aikins, M. (2002). An evolving theoretical framework for an epistemological beliefs system. In B. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp. 103–177). Mahwah, NJ: Erlbaum.

Schoon, K. J., & Boone, W. J. (1998). Self-efficacy and alternative conceptions of science of preservice elementary teachers. *Science Education, 82*(5), 553–568.

Schraw, G., & Moshman, D. (1995). Metacognitive theories. *Educational Psychology Review, 7*(4), 351–371.

Schraw, G., & Olafson, L. J. (2002). Teachers' epistemological world views and educational practices. *Issues in Education, 8*(2), 99–148.

Schunk, D. (1996). Goal and self-evaluative influences during children's cognitive skill learning. *American Educational Research Journal, 33*(2), 359–382.

Shepardson, D. P. (1999). The role of anomalous data in restructuring fourth graders' frameworks for understanding electric circuits. *Journal of Science Education, 21*(1), 77–94.

Stratford, S. J. (1997). A review of computer-based model research in precollege science classrooms. *Journal of Computers in Mathematics and Science Teaching, 16*(1), 3–23.

Tabachnick, B. R., & Zeichner, K. M. (1999). Idea and action: Action research and the development of conceptual change teaching of science. *Science Education, 83*(3), 309–322.

Thomas, G. P., & McRobbie, C. J. (1999). Using metaphors to probe students' conceptions of chemistry learning. *International Journal of Science Education, 21*(6), 667–685.

Thomas, G. P., & McRobbie, C. J. (2001). Using a metaphor for learning to improve students' metacognition in the chemistry classroom. *Journal of Research in Science Teaching, 38*(2), 222–259.

Tobin, K., & Tippins, D. J. (1996). Metaphors as seeds for conceptual change and the improvement of science teaching. *Science Education, 80*(6), 711–730.

Toth, E. E., Suthers, D. D., & Lesgold, A. M. (2002). The effects of representational guidance and reflective assessment on scientific inquiry. *Science Education, 86*(2), 264–286.

Tsai, C. (2001). Collaboratively developing instructional activities of conceptual change through the Internet: Science teachers' perspective. *British Journal of Educational Technology, 32*(5), 619–622.

Tsai, C. (2002). Collaboratively developing instructional activities of conceptual change through the Internet: Science teachers' perspective. *British Journal of Educational Technology, 32*(5), 619–622.

Van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modeling in science. *International Journal of Science Education, 21*(11), 1141–1153.

Van See, E. H. (2000). Analysis of a student-generated discussion. *Journal of Science Education, 22*(2), 115–142.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45–69.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds. and Trans.). Cambridge, MA: Harvard University Press.

Weaver, G. C. (1998). Strategies in K-12 science instruction to promote conceptual change. *Science Education, 82*(4), 455–472.

Webb, N. W., & Palincsar, A. S. (1996). Group processes in the classroom. In D. C. Berliner & R. C. Calfee (Eds.), *The handbook of educational psychology* (pp. 841–873). New York: Macmillan.

White, B. C. (2000). Pre-service teachers' epistemology viewed through perspectives on problematic classroom situations. *Journal of Education for Teaching, 26*(3), 279–305.

White, R. T. (1998). Decisions and problems in research on metacognition. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 1207–1213). New York: Kluwer Academic Publishers.

White, R. T., & Mitchell, I. J. (1994). Metacognition and the quality of learning. *Studies in Science Education, 23*(1), 21–37.

Windschitl, M. (2002). Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education, 87*(1), 112–143.

Zembal-Saul, C., Blumenfeld, P., & Krajcik, J. (2000). Influence of guided cycles of planning, teaching, and reflection on prospective elementary teachers' science content representations. *Journal of Research in Science Teaching, 37*(4), 318–339.

Zimmerman, B. (2000). Attaining self-regulated learning: A social-cognitive perspective. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 13–39). San Diego, CA: Academic Press.