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## The Role of Metacognition in Learning Chemistry

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Metacognition is a term that has been used in the psychology and education research literature since the mid-1970s. Flavell defined metacognition as "knowledge concerning one's own cognitive processes and products or anything related to them" and stated that "Metacognition refers, among other things, to the active monitoring and consequent regulation and orchestration of these processes in relation to the cognitive objects or data on which they bear" (1, p 232). Although it can be interpreted simply as *thinking about one's own thinking*, metacognition is a complex construct that plays a central role in theories of conceptual change, in particular those aligned with constructivist perspectives on learning and guided-discovery methods of instruction. In a 1988 review, R. T. White identified the following four facets of metacognition: (i) propositional knowledge about cognition (e.g., knowledge of the factors that affect ability to memorize something), (ii) awareness of one's own thoughts (e.g., monitoring one's own understanding during a lecture), (iii) ability to regulate thinking (e.g., deciding what path to take while attempting to solve a difficult problem), and (iv) readiness/propensity to apply the ability to regulate thinking (2). In this paper, we explain why it is important for chemistry educators to know about metacognition, provide some examples to illustrate our points, and discuss some instructional tools that have been employed to promote metacognition in introductory science courses.

First, it should be emphasized that metacognition is a more specific term than *reflection*. Metacognitive activities differ from such general cognitive processes in that, for metacognition, the object of reflection is always one's personal knowledge or thinking. This distinction is often difficult to make, however, since cognition rarely occurs in the complete absence of metacognition. Flavell pointed out that "Asking yourself questions about the chapter might function either to improve your knowledge (a *cognitive* function) or to monitor it (a *metacognitive* function)" (1). As an additional illustration,

compare the following (nonsequential) statements made by general chemistry students while attempting to solve a problem.

*Statement 1:* "Cause pressure is just the number of molecules. It's not like the size of them."

*Statement 2:* "But I don't see how we use partial pressures to find out the reaction. Do you know what I'm saying? The stoichiometry?"

Although statement 1 shows more evidence of *cognition* relating to the idea of partial pressures, statement 2 is more *metacognitive*, as it indicates the student's awareness of her own thoughts and her attempt to regulate the direction taken in the problem-solving process. Distinguishing the metacognitive from the cognitive is also difficult because the processes of interest are internal and can only be inferred on the basis of observations of student behavior.

### The Importance of Metacognition in Chemistry Education

Metacognition is generally thought to be a key to deeper, more durable, and more transferable learning. It is important for chemical educators to understand for at least two reasons: awareness of one's own thoughts is important for developing an understanding of ideas (3–5), and awareness and control of thinking have been shown to have a significant impact on problem-solving success (1, 6).

#### Understanding Ideas

The literature on conceptual change in science characterizes students' science ideas and advances various theories about how better understanding may be fostered (5, 7–22). An ongoing debate in conceptual change theory concerns whether students' naive science knowledge is coherent and theory-like ("theory theory") or fragmented and context-bound ("pieces theory"). Proponents of the theory theory view (9, 12, 17, 19, 21, 22) see the development of science knowledge in students as similar to revolutionary changes in the history of science, in which old theories are abandoned and replaced with more fruitful ones. On the other hand, supporters of pieces theory (13–15, 20, 23, 24) describe students' process of con-

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ceptual change as a more evolutionary reorganization and refinement of their knowledge.

While the degree of coherence of students' naive science knowledge has implications for instruction, the idea that awareness of their own thoughts helps students develop their understanding of science concepts is consistent with both theory theory and pieces theory views of conceptual change. Whether students' knowledge is coherent or fragmented and context-bound, a keen awareness of their own conceptions should allow students to recognize when their ideas are not productive or cannot be reconciled with data or ideas presented by others. Students with high levels of metacognitive activity are therefore more able and more likely to refine naive ideas in the face of contradictory experimental results. In addition, before students can seek explanations or decide that further reflection upon a topic is required for understanding, they must realize in what ways their understanding of concepts is incomplete. Thus, students' own monitoring of their developing understanding of new concepts is essential for effective learning. Awareness of how various concepts and principles fit together also tends to lead to greater coherence of knowledge (25).

Along the continuum of instructional philosophies from teacher-controlled didactic teaching to student-controlled discovery learning, guided-discovery approaches maximize the likelihood that students will engage in fruitful metacognitive activity (5, 8, 26). Studies of students' understanding of science ideas after instruction provide clear evidence that traditional didactic teaching methods are not very successful at bringing about productive changes in students' conceptions (27–33). Although didactic styles of instruction have been shown to be reasonably successful at imparting the facts, rules, procedures, and algorithms of a domain (7), they are not effective for helping students refine and build on their ideas about science concepts—in part because they neither require nor encourage high levels of student metacognition. Typically, students are simply told the “correct” scientific ideas and are expected to understand them despite the fact that they are given few opportunities and little guidance to develop such an understanding. Students are not likely to change ideas constructed from a lifetime of experience simply because an instructor or text informs them of scientists' ideas. In his discussion of recent research on learning and instruction, White points out that years of attempts to teach physics through this so-called *transmission model* have failed miserably: “investigations revealed a depressingly shallow quality of learning. Although students could manipulate complex formulae and could work through involved exercises, they often did not understand fundamental principles” (5, p 155).

At the opposite end of the spectrum are “pure” discovery-learning approaches to instruction. Proponents of pure discovery believe that students should be encouraged to explore their environments creatively and that these explorations should not be curriculum-driven, but based on the interests of the students (34). However, like didactic approaches, discovery learning methods also fail to encourage student reflection. In fact, unguided discovery-learning methods rely on the assumption that students already possess advanced metacognitive abilities (5, 35). Students in highly unstructured environments are never forced to confront their misconceptions, nor are they given the opportunity to reconcile them with

scientific conceptions. In addition, pure discovery methods lack sufficient guidance, and students may end up confused, not knowing what to do for long periods of time. In fact, a high degree of open-endedness in chemistry lab classes has been found to be significantly *negatively* correlated with achievement on chemistry examinations (36). The goal of a guided-discovery learning environment is to strike an appropriate balance between didactic teaching and discovery learning, allowing students to take a large measure of responsibility for their own learning but also requiring them to reflect upon and explain their ideas and justify their conclusions.

### Problem Solving

A second reason why metacognition is of interest to chemical educators is that good monitoring and regulation of thinking can improve success in problem solving. In studies of problem solving in college mathematics, Schoenfeld found that in addition to content knowledge there were several other important components of successful problem solving (6). Students' problem solving was also influenced by the use of problem-solving heuristics (“rules of thumb”), monitoring and control (metacognition), beliefs and affects, and communities of practice (groups of people engaged in common endeavors within their own culture).

Schoenfeld and others who have studied problem solving have pointed out that the term has been defined in multiple ways and used in many different contexts. Although Schoenfeld gives several illustrations of ways in which *problem solving* has been used, two opposing interpretations are of interest here. The first is the “traditional” definition in which problem solving is “working the tasks that have been set before you”; it is this usage that conjures up visions of tedious general chemistry exercises. The contrasting definition of problem solving put forth by Schoenfeld is “learning to grapple with new and unfamiliar tasks, when the relevant solution methods (even if only partly mastered) are not known”. This second sense of mathematical problem solving is the one for which metacognitive skills are vital. Here we provide an example comparing the problem-solving process of a chemistry graduate student with that of an undergraduate pair (S1 and S2) enrolled in first-semester general chemistry to illustrate that metacognition is also a key component of successful chemistry problem-solving.

A graduate student and an undergraduate pair were asked to verbalize their thoughts (37) while they solved some chemistry problems. They were left to solve the problems uninterrupted and no time limit was set. The undergraduate students were asked to work together to ease the stress of being videotaped while solving a difficult problem. The first problem the students were asked to solve was a standard, straightforward chemistry exercise intended to relax the participants and build their confidence. The second problem (38, 39) was a nonstandard one that did not require extensive chemistry knowledge for its solution (see the Box). If the students did not answer the nonstandard problem correctly, they were asked to attempt a third problem (40), which was a standard exercise requiring the use of the same chemical principle needed for the solution of the nonstandard problem.

The graduate student approached the nonstandard problem in the following way. She read the problem, formulated an implicit plan, and immediately moved on to implementation.

**Nonstandard Problem**

A sample of a compound of xenon and fluorine was confined in a bulb with a pressure of 24 torr. Hydrogen was added to the bulb until the pressure was 96 torr. Passage of an electric spark through the mixture produced Xe and HF. After the HF was removed by reaction with solid KOH, the final pressure of xenon and unreacted hydrogen in the bulb was 48 torr. What is the empirical formula of the xenon fluoride in the original sample?

**Standard Analog**

A mixture of 17.1 g of  $\text{CO}_2$  and 8.65 g of Ne exerts a pressure of 549 torr. Find the partial pressure of each gas in the mixture.

However, in the process, she made an incorrect assumption (that the total pressure after the reaction would be equal to the total pressure before the reaction) and didn't seem to give it a second thought:

"So we want to know the empirical formula of xenon fluoride. And we took out—we started—we had a total of 96 torr to start with and we removed 96 minus 48 torr—96 minus 48—is also 48 torr. And this removed all the fluoride, so then we had 48 torr of HF. And if we had 48 torr of HF—48 torr of HF was removed, which equals all of the fluoride, and we started with 24 torr of xenon some unknown fluoride... is the total. So the empirical formula has to be xenon difluoride."

Interestingly, the assumption that she made was false because of the same principle she later used to rationalize the empirical formula for xenon fluoride—that pressure is directly proportional to the number of moles of gas. If it is possible that the total number of moles of gas is different after the reaction, then it is also possible that the total pressure is different. The graduate student neglected to consider the possibility (in fact, the probability) that the number of moles of gas changed when the reaction took place. She completed her solution in about three minutes, made no attempt to verify her answer, and came to an incorrect conclusion. She overlooked an important connection that she probably would have realized if she had written out the balanced chemical equation for the process that she described. Not only did this graduate student neglect to consider her assumptions carefully before jumping into a solution, but she also failed to use the most basic of chemistry heuristics (writing the balanced chemical equation). In addition, it was clear from the data collected that the graduate student possessed the domain knowledge necessary to solve the problem (in particular, that under conditions of constant temperature and volume, pressure is proportional to moles of gas), and she solved the standard analog correctly. Thus, we can plainly see that poor monitoring and control led the graduate student to failure on this problem.

In contrast, the problem-solving success of a pair of undergraduate students illustrates how metacognition can help compensate for a lack of experience in dealing with chemistry problems. The undergraduates began by exploring the problem in a fashion similar to that of many who were unsuccessful at solving it. One important difference, however, was that S2 made good use of her metacognitive skills and tended

to keep the pair on task. From the start, S1 was tempted to just try her first idea, but S2 was determined that they make progress toward their ultimate goal. The following exchange occurred immediately after the students read the problem:

S2: Okay, well we have to figure out ... Let's see ...

S1: So, what if we started with ...

S2: We have to figure out how much reacted with how much, to figure out like the equation, so we can figure out the stoichiometry.

S1: Right.

S2: ... to figure out ... Okay, so ...

S1: But—so here we just find—we assume they're half? Do you know what I'm—?

S2: No, I don't think we can...

S1: Hydrogen was added 'til the pressure was 96. So you can—you know how much hydrogen you have, right? Can you subtract them or do you have to get them into some equation?

S2: For what?

Throughout the problem-solving session, S2 frequently asked questions like "How do we use the partial pressures to figure out the stoichiometry?" or responded to S1's attempts at wild goose chases with comments like "But I don't see what that tells us." Interestingly, at one point, the undergraduate students made the same faulty assumption that led the graduate student to failure. What saved the undergraduates here was that S2 did not allow S1 to pursue that path because she didn't see how figuring out more partial pressures would lead them to the mole ratios. Later in the problem-solving session, the two concluded that the previously made assumption was false.

Approximately 17 minutes into the problem-solving session, the undergraduates realized that what they had been doing wasn't getting them anywhere. At this point they decided to start over, and they had a discussion that seemed to help them get a conceptual picture of what was happening (in contrast to S1's previous attempts to simply find the right formula, plug, and chug). This discussion helped them make connections that were key to their later success. The pair also continued to do a very good job of monitoring their work. A few minutes later, the undergraduates decided to try S2's suggestion of using the pressure values as the number of moles. Since they didn't see how they could do this using the variables in the formula  $\text{Xe}_x\text{F}_y$ , they instead began by suggesting a chemical formula and testing it out. This was quite a reasonable approach, since they knew that  $\text{XeF}_6$  and  $\text{XeF}_4$  were xenon-fluoride compounds, and they were able to determine that  $\text{XeF}_4$  was the correct empirical formula.

Comparison of the problem-solving processes of the chemistry graduate student and the undergraduate pair provides evidence that metacognition is important for success in solving nonstandard chemistry problems. Insufficient metacognitive skills caused the graduate student to fail to solve a problem for which she clearly possessed the relevant domain knowledge. The graduate student did not succeed at solving the nonstandard problem because she did not stop to examine how her ideas about different aspects of the problem fit together, perhaps to some extent because she mistakenly believed she had a good understanding of the problem. On

the other hand, good use of metacognitive skills, which may be partly attributed to the fact they were working collaboratively, enabled first-semester general chemistry students with only 12 weeks experience to solve the same problem. These findings imply that promoting metacognition as one aspect of thinking like a scientist is as important as emphasizing the content aspects of chemical problems. They also point to the need to distinguish lack of knowledge of chemical principles from deficiencies in understanding and using that knowledge appropriately.

### *Is It Chemistry Instructors' Responsibility to Develop Students' Metacognitive Skills?*

Even if the preceding discussion has convinced you of the importance of metacognition in chemistry learning and problem solving, you may be questioning whether it is the responsibility of chemistry instructors to develop students' metacognitive skills. It appears that if the goal of enhanced student understanding of chemistry is to be achieved, chemistry instructors will need to include instruction on the use of relevant thinking strategies in their courses. First, research suggests that teaching general "critical thinking" skills divorced from content knowledge is not sufficient to allow students to transfer those skills to new situations and types of problems. While some transfer of general thinking skills is possible, it is relatively rare and is achieved only under particular instructional conditions (41, 42).

In addition, since each discipline has characteristic ways of reasoning, some general metacognitive strategies are applied slightly differently in different domains, and many of the most useful metacognitive strategies are domain specific (41, 42). An example of a general thinking strategy is evaluating new ideas by comparing them with other things you know about to see if the ideas fit together and make sense to you. A strategy more specific to the domain of chemistry is making connections between macroscopic observations and molecular-level explanations. Clearly, both general and domain-specific strategies are essential for developing a high-quality understanding of chemistry. Thus, infusion of teaching of metacognitive skills in subject matter areas, in addition to general teaching of metacognitive skills in schools, is a promising approach to helping students learn to use their content knowledge more appropriately and flexibly (41, 42).

### **Instructional Tools for Promoting Metacognition**

The development of instructional methods that would improve the conceptual understanding and problem-solving abilities of students in science classes has long been a goal of science instructors and science education researchers. Because promoting metacognition in the classroom seems like a promising way to achieve these goals, some science instructors have begun to implement instructional methods intended to encourage students to be more metacognitive. In introductory college science courses, these efforts focus on making students more aware of their own ideas, and include the use of such instructional tools as concept maps, ConcepTests, Predict–Observe–Explain (POE) tasks, and the Model–Observe–Reflect–Explain (MORE) Thinking Frame. In the following sections, we briefly describe each of these tools and summarize the results of studies of their instructional effectiveness.

### **Concept Maps**

Efforts to promote metacognition in chemistry courses have often focused on making students aware of their ideas through the use of concept maps (43–47). Concept mapping, which was developed by Novak and Gowin (48), involves the construction of a diagram that emphasizes relationships between concepts.

Two recently published research studies focused on the effects of having students construct concept maps before and after each chemistry laboratory session. One study involved 180 high school students (43) and the other involved 32 college students (47). On tests designed to measure conceptual understanding, neither study found significant differences in achievement between the concept map group and the control group (in which students performed the same lab experiments but did not construct concept maps). In addition, the study involving college students found that, for students with high verbal abilities, concept mapping actually interfered with comprehension of chemistry ideas (47). Thus, although the use of concept maps may confer other benefits (46, 47), their use as add-ons in the chemistry laboratory course has not been shown to be an effective method of improving students' understanding.

### **ConcepTests**

The ConcepTest is another metacognitively focused instructional tool that many chemistry instructors have recently adopted. ConcepTests are multiple-choice questions carefully constructed to expose student ideas that are at odds with scientifically accepted views. Students are presented with a question during a lecture and asked to vote on the answer. After this initial vote, students are allowed time to discuss the question with others around them before a final vote is taken, and any shift in the most popular answer is observed. The ConcepTest ends with the instructor's explanation of his or her thinking about the question.

The activity structure ("peer instruction") used in the ConcepTest was developed by physicist Eric Mazur for his lectures at Harvard University. Mazur has found that lectures taught using peer instruction improve students' conceptual understanding and problem solving in mechanics (49). Thus far, no studies of the instructional effectiveness of using ConcepTests during chemistry lectures have been published.

### **Predict–Observe–Explain (POE) Tasks**

Endeavoring to assess students' understanding of classical mechanics, Champagne, Klopfer, and Anderson (50) developed what is now known as the POE task (51). Using POE, students make predictions about an event and explain the reasons for their predictions; this highlights their initial ideas. Then they observe a demonstration or conduct a laboratory experiment and are required to reconcile their observations with their predictions; this is intended to get students thinking about the phenomena being studied and cause them to reexamine their initial ideas.

POE-based instructional approaches have been successful in promoting conceptual change in physics (16, 18, 52). However, the work of White and Gunstone (51, 53) illustrates that caution should be taken with the POE approach with respect to the effect of students' predictions on their observations: students who make incorrect predictions often interpret their

experimental results to align with those predictions. For example, students who initially believed there was a linear relationship between voltage and current drew linear graphs based on data that clearly indicated a curved relationship (53). One way to combat this problem is to ask groups of students to pool their data and try to agree on a common set of observations.

### *The Model–Observe–Reflect–Explain (MORE) Thinking Frame*

The MORE chemistry laboratory course was designed to promote metacognition in a guided-discovery environment while encouraging students to explore chemistry concepts through authentic scientific inquiry. The problem-based curriculum for the course consisted of three multiweek modules, each focusing on an overarching question that motivated specific experimental questions within the broader topic. The instruction for the course was built around the MORE Thinking Frame (discussed in detail in ref 54), which is an adaptation of the POE task intended to get at the goals of the course by providing students with a framework to guide their thinking. For a general discussion of thinking frames, see ref 55.

The MORE Thinking Frame differs from the POE task in a several important ways. First, students begin a laboratory module by representing their initial ideas about the experimental system as a whole (their initial model). This requires students to reflect on their ideas about various aspects of the chemical system rather than on an isolated experimental outcome. Second, the MORE Thinking Frame includes an explicit reflection component. Third, the MORE Thinking Frame includes the idea of model refinement. Thus, after each experiment in a module, students are explicitly prompted to reflect upon the implications of their observations for their model and revise their ideas accordingly. Finally, although the MORE Thinking Frame could be used to guide students through inquiry in any discipline, its instantiation in the MORE laboratory program emphasized chemistry-specific metacognitive strategies such as connecting macroscopic observations with atomic- and molecular-level explanations.

Results of a study comparing the learning of students enrolled in the MORE course with that of students in standard lab sections show that the MORE students developed significantly enhanced metacognitive abilities, understanding of fundamental chemistry ideas, and abilities to solve examination problems (56). This work provides a concrete example for chemists of how a metacognitively focused instructional tool can be effectively employed in the general chemistry course.

### **Future Research Directions**

Metacognition is undoubtedly an indispensable aspect of chemists' thinking and students' learning about chemistry. Yet, perhaps owing to lack of awareness of the importance of metacognition, or alternatively, the belief that it is not the responsibility of science instructors to foster metacognitive abilities, little research to this point has addressed issues related to the role of metacognition in understanding chemistry. While it is clear that, in general, metacognition contributes favorably to chemistry learning, many open questions about its specific role remain. Some issues for future research in chemical education are (i) how can metacognition best be promoted in chemistry courses (especially in "lecture" situations)? (ii) how can metacognitive aspects of chemistry learn-

ing best be assessed? and (iii) how are the various aspects of metacognition related to chemistry learning outcomes? Because methods for improving chemistry-specific metacognition enhance the ability of chemistry learners and practitioners to use their content knowledge more appropriately and flexibly to solve problems, research in this as yet unexplored area promises to bring intriguing and important insights to the field of chemistry.

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## Simulations for Teaching Chemical Equilibrium

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Analogies are not new to science; they have been used through the ages by both scientists and students to help them understand theoretical concepts (1). However, in recent years renewed attention has been given to the role of analogies in science teaching (2) and it has been suggested (3) that the goal of science education research should be to invent analogies and evaluate their effectiveness in science lessons. These analogies may be verbal or may involve actual physical experiences, diagrams, simulation experiments, and even computer-assisted activities.

Ausubel (4) was the first to suggest that students need to relate new knowledge into existing mental structures for meaningful learning to occur and for students to be able to apply the knowledge to other situations. Concrete examples are easier to integrate into existing knowledge than abstract ones and, if carefully chosen and presented, can enhance the intelligibility and plausibility of explanations (5). Certain topics in chemistry are highly theoretical and give learners great difficulty (6). Thus, the teaching of chemistry lends itself to the use of analogies to explain abstract concepts (7, 8) where the analogies are generally recognized to generate meaning through a constructivist pathway (9). Not surprisingly, findings by researchers (7, 10) show that analogies may be more effective for students of lower formal reasoning and are less useful for more capable students who have probably already reached the formal operational stage of development (11). Results of studies in the classroom (7) show that the use of analogies is infrequent and less effective than it might

be but that a competent teacher can systematically integrate analogies into her classroom practice (12).

Chemical equilibrium is rated as the most difficult concept for students to comprehend (13, 14) and one of the more difficult sections of physical science to teach (15–17). It is therefore not surprising that it is a topic in which teachers frequently use analogies and in which analogies are often cited in textbooks (7). The analogies themselves may lead to or reinforce alternate conceptions (18). For example, the often used analogy of water flowing in and out of a sink to show the constant dynamic properties of a steady-state open system (7) does not accurately mimic chemical equilibrium. In fact, it may reinforce the documented alternate conception in equilibrium (13) that the forward reaction goes to completion before the reverse reaction commences.

Harrison and Treagust (18) emphasize the need for a systematic approach when using analogies and the need to map out similarities and differences between the analogy and target (the science concept being studied) to prevent further alternate conceptions from arising in the minds of students during the use of an analogy.

An in-depth study carried out at the University of the Witwatersrand (Wits), Johannesburg, South Africa, revealed that our first-year students espouse most of the common alternate conceptions in chemical equilibrium (19). Studies by Bradley with student teachers in South Africa showed that these alternate conceptions were not remedied by three years of study of chemistry at a tertiary institution (20). Bradley's