Connecting Concepts with Procedures in Equilibrium
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Connecting Concepts with Procedures in Equilibrium Instruction: Evaluating the Majority and Minority (M&M) Strategy

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ABSTRACT: Two studies are presented relating to a set of instructional suggestions for teaching chemical equilibrium. In the first study, we used techniques from the field of cognitive science to answer the question; “Do experts invoke Majority/Minority (M&M) reasoning during equilibrium problem solving?” To determine whether and how experts reason differently from students as they solve problems, we asked experts (chemistry professors and advanced graduate students) and novices (college undergraduates) to think aloud as they solved equilibrium problems. Analysis of this data revealed that experts were more likely than novices to invoke progress of reaction type reasoning and to demonstrate planning though using an approximation strategy. Results from this study also suggest that the M&M strategy is aligned with expert reasoning and problem solving strategies. In the second study, we compared students’ exam data in two different semesters using a quasi-experimental design to evaluate whether the M&M strategy was learnable and whether instruction using the strategy improved equilibrium problem solving. Our results demonstrate that the M&M strategy is aligned with expert reasoning and problem-solving, is learnable by students and promotes problem solving performance.

INTRODUCTION

The aim of chemistry instruction is more than memorizing facts or procedures, instead, instructors would like students to acquire the core principles, reasoning and thinking skills used by experts in the domain. Much of typical chemistry instruction and assessment consists of quantitative problem solving activities with the implicit assumption that students are learning core concepts in chemistry through the manipulation of numbers and symbols. Successful performance on complex calculations is taken as evidence that students have mastered topics in the domain. However, research in chemistry education casts doubts on the notion that quantitative ability reflects conceptual understanding. A number of studies have demonstrated that students have great difficulty connecting the mathematical representations with the underlying chemistry concepts and that even high achieving students may lack basic knowledge of core principles (e.g., Bodner and Herron, 2002; Gabel and Bunce, 1994; Nakhleh and Mitchell, 1993; Nurrenbern and Pickering, 1987; Phelps, 1996; Smith and Metz, 1996). For instance, Smith and Metz (1996) found that students who had performed well on traditional assessments in acid/base chemistry were unable to identify strong versus weak acids when shown diagrams, suggesting that they had memorized definitions and used terms without true comprehension. Nakhleh and Mitchell (1993) similarly found conceptual understanding lacking, even when students could successfully solve algorithmic problems. Half of the students with high algorithmic performance had low conceptual performance. These data suggest that emphasizing algorithmic problem solving and quantitative procedures does not
adequately prepare students with the conceptual understanding they need to reason in chemistry. Yet many introductory courses devote weeks to units on equilibrium and related topics of acid/base chemistry with a focus on quantitative problem solving. Such equilibrium problem solving is difficult for students to master, and some have suggested that teaching complicated, multi-step procedures to students in introductory classes may be a poor use of instructional time (e.g., Hawkes, 1999).

The Majority Minority (M&M) strategy, described in the preceding paper by Yaron et al. (2010) in this issue, is an attempt to help students connect quantitative calculations with conceptual understanding of the meaning behind the calculations. The claims are that the M&M strategy is an approach implicitly used by experts in the field of chemistry to reason about equilibrium systems, that the new strategy is learnable by students, and finally, that the strategy will improve student problem solving success. In the current paper, we describe two empirical studies to test these claims.

In the first study, we use techniques from the field of cognitive science to answer the question; “Do experts invoke M&M reasoning during equilibrium problem solving?” To determine whether and how experts reason differently from students as they solve problems, we asked experts (chemistry professors and advanced graduate students) and novices (college undergraduates) to think aloud as they solved equilibrium problems. This expert-novice comparison allowed us to verify that experts were more likely to use M&M type reasoning and helped us to better understand student procedural and conceptual errors. In the second study, we compared students in two different semesters using a quasi-experimental design to evaluate whether the M&M strategy was learnable and whether instruction using the strategy improved equilibrium problem solving.

For both studies we use the following equilibrium problem as the basis of our research:

Consider the following reaction: 3A + 4B ⇌ 2C, K = 1.2 x 10^6

100 ml of 1.2M A is mixed with 50 ml of 1.8MB. What is [A], [B] & [C] when the system reaches equilibrium?

We selected this problem as it meets three criteria. First, the equilibrium system has a strong (K>>1) forward reaction, which makes the problem a good candidate for an approximation strategy. Secondly, the coefficients of the chemical species make a “plug and chug” strategy difficult. As the exponents lead to difficult computations, we are able to identify which problem solvers are applying meaning to problem solving, and which are performing purely algorithmic procedures. Finally, the problem was sufficiently complex, so we were able to gain insight into the reasoning behind the problem solving through verbal protocol analysis and an investigation of problem-solving steps.

STUDY 1 – DO EXPERTS USE M&M REASONING WHEN SOLVING PROBLEMS ABOUT EQUILIBRIUM?

The goal of the expert/novice study was to identify whether experts use reasoning similar to the M&M strategy. Critically, the M&M strategy involves integrating conceptual information with problem solving in two ways. First, M&M reasoning involves an understanding that the reaction in an equilibrium system describes ongoing chemical processes that lead to steady concentrations of chemical species at equilibrium. The changes in concentration as the system reaches equilibrium is referred to as the “progress of reaction.” In problem solving, evidence of this understanding is manifest when problem-solvers invoke the law of mass action expression (K=Q) using equilibrium concentration values, rather than the initial concentrations provided in the prompt. Second, the M&M strategy takes advantage of an approximate solution, based on an initial planning step that identifies which chemical species will be majority (i.e.,
have a high concentration) and which will be minority (i.e., have a low concentration) at equilibrium.

Expertise encompasses more than just knowledge, it also reflects how the knowledge is structured and applied (Feltovich et al., 2006). To investigate whether experts use M&M reasoning during equilibrium problem solving, we carried out a “think aloud” study using verbal protocol analysis. In a think aloud study, participants are asked to say everything they are thinking as they complete a task, and audio is recorded for subsequent analysis. Research suggests that think-alouds are highly effective at revealing reasoning strategies, and are not likely to interfere with problem solving as long as participants are not asked to explain their reasoning (Ericsson and Simon, 1984, 1993; Newell and Simon, 1972).

Research comparing expert and novice problem solving has found that that while experts apply core principles as they solve problems, novices tend to focus on surface features (e.g., Chi et al. 1981; Kozma et al., 2000). Experts and novices solve problems very differently from one another. Many studies of expertise have been conducted in the domain of physics and typically define experts as advanced graduate students or instructors and novices as students with recent instruction in the domain. The findings show that experts categorize problems based on core principles, use domain knowledge in the form of principle-based schemas to guide problem solving, and plan solution strategies at an intermediate level of detail. Novices, on the other hand, categorize problems based on surface features, use calculation-based schemas to guide problem solving and plan solution strategies in overly vague or specific terms (e.g., Chi et al., 1981; Larkin, 1987; Priest and Lindsay, 1992; VanLehn and Van de Sande, 2009).

In the current study, we hypothesized that experts would be more likely than novices to use M&M type reasoning. We operationalized M&M reasoning as 1) demonstrating an understanding of the “progress of reaction” by integrating concepts with problem solving, and 2) demonstrating planning through using an approximation strategy for an equilibrium system that progresses nearly to completion. We evaluated both the written problem solving steps, as well as verbal reasoning made explicit in the think alouds.

To determine whether solvers were integrating concepts with procedures, we evaluated both written work and reasoning. As novices tend to focus on surface features, they tend to use shallow, “plug and chug” strategies without considering conceptually whether the answer makes sense. Prior research suggests that students, who were taught with primarily procedural methods such as limiting reagent problems, tend to make errors that reveal they interpret the chemical equation as indicating the species present in solution before and after reaction, rather than interpreting the reaction as a rule for how molecules combine to form new species (Yaron et al., 2010). To solve the problem, solvers must think through the progress of reaction and invoke the law of mass action, \( K = \frac{[C]^2}{[A]^3[B]^4} \) at equilibrium. Students using a shallow strategy “solve” for the answer by instead inputting initial concentrations from the problem statement. We sought further evidence that solvers were connecting conceptual information related to the progress of the reaction in the verbal protocol analysis. In particular, we hypothesized that experts would be more likely to explicitly describe the progress of reaction as they refer to chemical reactions dynamically (e.g., revealing an understanding that the concentrations are changing along a continuum), rather than referring to various states of the system (e.g., the initial state, the final state).

To determine whether solvers demonstrated planning, we looked for use of a two-step approximation strategy that first runs the reaction to completion to identify the limiting reagent, and then runs the reverse reaction to determine concentrations of minority species. Both non-approximate and approximate strategies for determining equilibrium concentrations are taught in introductory chemistry classes. These strategy
differences allow us to investigate differences in problem solving. The non-approximate strategy introduces a variable x to account for the progress of reaction away from initial concentrations. Due to the exponents in the resulting law of mass action, this leads to the difficult math of finding the root of a high order polynomial. The second strategy uses an approximation that reflects deeper conceptual understanding by applying information about the magnitude of K, the equilibrium constant, to approximate equilibrium concentrations. For instance, if the equilibrium constant is very large (e.g., $K = 1.2 \times 10^6 = \frac{[C]^2}{[A]^3[B]^4}$), then the equilibrium concentrations will be approximately equal to the concentrations obtained if all As and Bs reacted until one type of molecule, the limiting reagent, ran out. As no concentrations can be equal to zero in an equilibrium system, the law of mass action can be used to solve for the equilibrium value of the limiting reagent.

**METHOD**

**Participants.**

Five experts and 10 novices had the option to be paid or receive course credit for participation in this study. Experts were 3 chemistry faculty members from Carnegie Mellon University who had recently taught introductory chemistry and 2 chemistry graduate students that served as teaching assistants for this course. Ten novices were undergraduate students from Carnegie Mellon University that had completed two semesters of introductory chemistry within the past year.

**Materials.**

The problem investigated in the current study was the second question in a packet of five questions related to chemical equilibrium. The problem was: Consider the following reaction: $3A + 4B \rightleftharpoons 2C$, $K = 1.2 \times 10^6$. 100 ml of 1.2M A is mixed with 50 ml of 1.8M B. What are the concentrations of A, B and C when the system reaches equilibrium?

**Design and Procedure.**

Participants were given instructions on verbal protocols using the script in Ericsson and Simon (1993) and were asked to think aloud as they worked through the problems. Participants were videotaped as they solved problems. They received one problem at a time and worked at their own pace.

**Analysis of Problems.**

Both written problem solutions and verbal protocols were coded for analysis. Solutions were coded for 1) **progress of reaction** – whether solvers used equilibrium concentrations (rather than initial concentrations) in the mass action formula and 2) **approximation** – whether solvers used an approximation strategy to determine equilibrium concentrations.

**Analysis of Verbal Protocols.**

Videotapes were transcribed and coded blind to condition. Utterances were coded for **state-based** or **reaction-based** language that revealed that solvers considered the representation behind the quantities being manipulated. Utterances were coded as **state-based** if they contained reference to possible state differences in concentration values. Words referring to state changes included “starting concentrations, initial concentrations, initial concentrations, etc.” For example, “Initial concentrations are going to be reduced. So, your initial concentration is going to be 100mls times 1.2 for A divided by total volume 150.”

Utterances were coded as **reaction-based** if they used words such as “reacts” or “progresses.” A richer representation of the quantities of concentration is the additional constraint that the possible states of concentrations exist along a continuum that is limited by the coefficients of the given chemical reaction. For example, “A, B and C react..."
in a 3 4 2 ratio” or “Equilibrium constant is very large, so what I’ll probably do when I set this up is have the thing go completely in the forward direction and then algebraically work backwards and see what changes there are.”

Across all participants, the majority of statements in the verbal protocols related to mathematical problem solving. For example, “1.2 to the third times 1.8 to the 4th. C squared solving by multiplying 1.2 times 1.2 times 10 to the 6th” or “Okay, moles of A divided by 3, 0.12 divided by 3, 0.04. Moles of B is 0.09 over 4.” As these statements do not distinguish between different types of reasoning, they were not included in our analyses.

RESULTS

Results from written problems.

An analysis of problem solutions revealed that experts were more likely to integrate concepts with problem solving as they correctly applied equilibrium values in the mass action formula. An independent samples t-test revealed that this difference was significant, $t(13) = 2.55, p < .05$. In addition, experts were more likely to demonstrate M&M type reasoning as they more frequently used the approximation strategy during problem solving, $t(13) = 3.61, p < .01$. See Table 1 and Figure 1 for examples of written solutions.

Overall, experts were more successful problem solvers than novices, however the difference between the two groups was not categorical. An inspection of the pattern of these data reveals three categories of problem solvers with overlapping performance for some experts and novices. While no novices were able to use the approximation strategy, 4 of the 10 were able to correctly apply equilibrium values when using the mass action formula. Further while no experts mistakenly applied initial values to the mass action formula, only 3 of the 5 experts were able to use the approximation strategy. The results suggest a development of expertise that is supported by the fact that the 2 experts who failed to use the approximation strategy were the chemistry graduate students whereas the 3 experts who used the more appropriate approximation strategy were chemistry faculty.

Table 1. Number of Experts and Novices that used equilibrium values in the mass action (K) formula and used the Approximation strategy.

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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>5*</td>
<td>0</td>
</tr>
<tr>
<td>Yes</td>
<td></td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Expert</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>0</td>
<td>0</td>
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*One student did not invoke the mass action formula in problem solving
Results from Verbal Protocol Analysis.

To determine whether deeper conceptual understanding was reflected in the language used by experts during problem solving, we coded protocols for state-based and reaction-based comments. Our hypothesis was that deeper conceptual understanding would be reflected in the words that participants used to refer to the quantities while problem solving and that experts would make a larger number of comments relating to the ongoing reactions of equilibrium systems. ANOVAs carried out with level of expertise (Novice vs. Expert) as a between-subjects variable revealed that experts made more state-based comments ($M = 4.6$) than novices ($M = 2.1$), $F(1,13) = 4.7$, $p < .05$, and experts made more reaction-based comments ($M = 3.0$) than novices ($M = .7$), $F(1,13) = 10.4$, $p < .01$. See Figure 2.

Figure 1. Left. Example of Novice problem solving. Right. Example of Expert problem solving.

Figure 2. Comparison of State and Reaction utterances for Experts and Novices.
DISCUSSION

This first study provides evidence that experts and novices approach equilibrium problem solving in qualitatively different ways. Experts were more likely than novices to invoke progress of reaction type reasoning and to demonstrate planning though using an approximation strategy. Whereas novice participants gave little evidence of applying conceptual understanding in selecting the appropriate concentrations for the mass action formula or in choosing a problem solving strategy, experts applied conceptual understanding of concentration quantities to select appropriate values when using the mass action formula and selected the approximation strategy.

An analysis of the verbal protocols suggests that problem solving expertise is related to conceptual understanding of the quantities involved in the calculations. Novices made very few statements that revealed any conceptual understanding of the concentration quantities and instead referred nearly exclusively to mathematical calculations. Experts made significantly more utterances related to the progress of reaction (suggesting that concentrations change along a continuum) and were most likely to use an approximation strategy that reflected this type of thinking. Taken together, the results suggest that the Majority/Minority strategy is aligned with expert reasoning and problem solving strategies.

Are novices incapable of learning problem solving strategies? The novice participants in our study had all passed college level chemistry with a grade of B or above, so they were all given instruction on these types of problems. Our hypothesis was that the poor memory for procedures and unsuccessful problem solving was due to traditional equilibrium instruction that emphasized multi-step procedures and instruction that was not grounded in conceptual understanding of the processes occurring in an equilibrium system. We then hypothesized that the Majority/Minority strategy, that integrates concepts with problem solving procedures and models expert planning, would be more readily learnable by students and result in more successful problem solving.

STUDY 2 – IS THE M&M STRATEGY LEARNABLE BY STUDENTS, AND DOES IT IMPROVE PROBLEM-SOLVING PERFORMANCE?

In the second study we used a quasi-experimental design to determine whether the M&M strategy is learnable by students and whether students that received M&M instruction would be more successful at solving equilibrium problems. We compared student problem solving performance over two different semesters of undergraduate chemistry. In the control semester, students were taught to solve equilibrium problems that involved a large K using the traditional, small-x approximation strategy (Brown, 2009). In the treatment semester, students were taught to solve equilibrium problems using the Majority/Minority strategy. If the M&M strategy was more readily learnable by students, we hypothesized that students would be more likely to demonstrate the ability to apply concepts to procedures by using equilibrium values in the mass action formula, and to demonstrate planning by using an approximation strategy for equilibrium reactions that progress nearly to completion. Further, if the M&M strategy improved problem solving performance, we hypothesized that a greater proportion of students would correctly determine the equilibrium concentrations.

METHODS

Participants.

Exam data was collected from 314 students enrolled in second semester college chemistry (Modern Chemistry 2) courses at Carnegie Mellon in two different semesters. In the control semester, data was collected from 139 students (71 females and 68...
males). In the treatment semester, data was collected from 171 students (81 females and 90 males).

Procedure.
In both semesters an approximation strategy for solving equilibrium problems was taught by Dr. David Yaron during lecture and was reviewed in a subsequent lecture. In the control semester, which occurred before the researchers had developed the M&M strategy, students were taught using the “small-x” strategy. After developing the new strategy, in the treatment semester, students were taught using the Majority/Minority strategy. A tablet PC was used during class and worked examples were projected while Dr. Yaron explained the solution steps. All written information during lecture was captured (e.g. all worked examples) and was made available for students to review after class. In both semesters, lecture notes that captured all written information were available on the course website for students to review after class. All participating students were given the same exam question that required them to calculate concentrations for chemical species at equilibrium.

Analysis.
Our analysis of the exam data looked at whether students demonstrated conceptual understanding by using equilibrium values in the mass action formula, whether they used an approximation strategy during problem solving, and finally, whether students were successful in finding all equilibrium concentrations. All student problems were coded by a research assistant blind to hypothesis.

RESULTS
The results suggest that a greater proportion of students taught the Majority/Minority succeeded on our three measures. Students taught the M&M strategy were more likely to use equilibrium values in the mass action formula, more likely to use the approximation strategy, and were more successful overall. A one-way ANOVA found that significantly more students in the M&M semester used equilibrium values in the mass action formula ($M = .80$) compared to students in the control semester ($M = .63$), $F(1,309) = 12.13, p < .001$. Significantly more students in the M&M semester used an approximation strategy ($M = .92$) compared with students given the small-x instruction ($M = .24$), $F(1,309) = 128.19, p < .001$. Finally, students given M&M instruction ($M = .50$) were significantly more likely to find all correct concentrations at equilibrium, compared with students in the small-x condition ($M = .17$), $F(1,309) = 39.7$, $p < .001$. See Figure 3.
DISCUSSION

Our results from this classroom study suggest that the M&M strategy led students to perform more like experts on solving equilibrium problems. Students in the M&M condition were more likely to correctly apply equilibrium values to the mass action equation, were more likely to use an approximation strategy for an equilibrium reaction that neared completion, and were more likely to be successful at solving for the correct equilibrium concentrations. One hypothesis could be that students in the M&M condition were more proficient overall. However, an analysis of data from midterms does not support that claim as students in the control condition scored statistically significantly higher on the first midterm (prior to equilibrium instruction) than students in the M&M group.

GENERAL DISCUSSION

The current studies demonstrate that the M&M strategy is aligned with expert reasoning and problem-solving, is learnable by students, and promotes problem solving performance. The M&M strategy couples concepts with procedures (e.g., applying equations with meaning rather than “plug-and-chug”), and promotes planning of problem solving (e.g., thinking through when an approximation strategy would be productive.) The classroom study reveals that students taught using the M&M strategy were more likely to demonstrate expert-type reasoning about the progress of reaction and were more successful at equilibrium problem solving.

Why is the M&M strategy more successful than the mathematically identical “small-x approximation” strategy? Our hypotheses is that explicitly connecting qualitative reasoning to problem solving steps was more successful as it allowed student to reason conceptually about what is happening in an equilibrium reaction rather than simply following a long series of algebraic manipulations. Research in cognitive science resoundingly suggests that you “learn what you practice” (e.g., Ambrose et al., 2010; Ericsson, 2006). Expert chemists routinely reason qualitatively about chemical reactions, and are fluent at integrating concepts with algorithmic manipulations.

For students to develop the ability to integrate concepts and procedures, the process must make core concepts explicit and give students practice with concept-based thinking. As discussed in the prior paper, the M&M strategy applies to a wide range of
chemical systems. Our hypothesis is that the repeated exposure to this strategy across units will help students make conceptual connections both between concepts and procedures as well as across topics such as equilibrium, acid-base chemistry, and solubility chemistry.

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