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Evidence-Based Approaches to Improving Chemical Equilibrium Instruction

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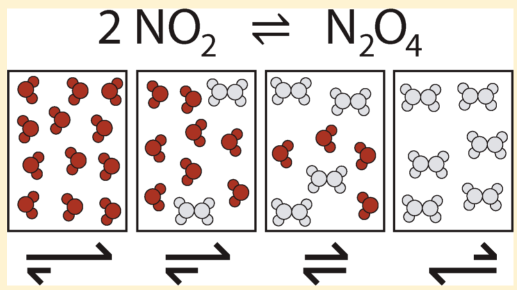
S Supporting Information

ABSTRACT: Two suggestions for instruction in chemical equilibrium are presented, along with the evidence that supports these suggestions. The first is to use diagrams to connect chemical reactions to the effects of reactions on concentrations. The second is the use of the majority and minority species (M&M) strategy to analyze chemical equilibrium systems. Two studies are presented in support of these suggestions.



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FEATURE: Chemical Education Research

■ INTRODUCTION

A goal of modern chemical instruction is to move students beyond memorizing facts and procedures and toward understanding and applying core principles of chemistry. For topics such as equilibrium, instruction has tended to emphasize quantitative problem solving, with successful performance on complex calculations taken as evidence that students have mastered the concepts. However, research in chemistry education suggests that quantitative ability is not always a result of conceptual understanding. Students have great difficulty connecting mathematical representations with underlying chemistry concepts, and even high achieving students may lack basic knowledge of core principles.[1−7] For instance, Smith and Metz[6] 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. Similarly, a study by Nakhleh and Mitchell[3] found that half of the students with high algorithmic performance had low conceptual performance.

In chemical education research, qualitative understanding of the dynamic nature of the equilibrium state has received considerable attention.[8−10] However, reasoning about concentrations in equilibrium systems is also an important aspect of mastery that requires knowledge beyond simply understanding that equilibrium systems are dynamic. This paper focuses on additional knowledge required to reason about equilibrium systems and puts forward two evidence-based suggestions for improving instruction: (1) make the progress of reaction explicit and (2) use the Majority/Minority (M&M) Strategy to frame both qualitative and quantitative analysis of equilibrium systems.

Following a description of the instructional strategies, we detail two studies in support of our instructional suggestions, and demonstrate the application of the M&M strategy to multiple reaction systems.

■ RECOMMENDATIONS FOR INSTRUCTION

Make the "Progress of Reaction" Explicit

The manner in which ongoing chemical reactions lead to changes in concentrations, though intuitive to experts, is something which should be made explicit in instruction.[11] The reaction may be viewed as a rule

$$2NO_2 \rightleftharpoons N_2O_4 \qquad (1)$$

applied to a collection of molecules to generate the "progress of reaction" (or "extent of reaction") shown in Figure 1.

The chemical reaction equation itself is often used as a shortcut when discussing phenomena that are associated with the progress of reaction. For instance, in LeChatelier's principle, the phrase "shifts to the right" is often stated while using the reaction equation as the only representation. By using collections of molecules, such as in Figure 1, instruction can make both the nature of the "stress" explicit (i.e., change in Q due to changes in concentration or change in K due to temperature) and the nature of the "shift" explicit (i.e., changes

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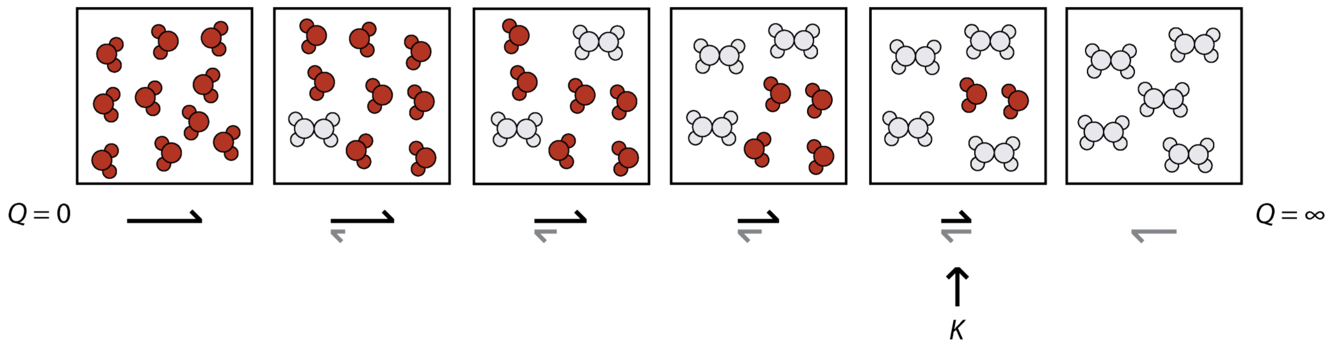

Figure 1. Schematic for the reaction $2NO_2 \rightleftharpoons N_2O_4$, showing the progress of reaction (from all reactants on the left to all products on the right), along with the connection to the reaction quotient Q, the rates of the forward and reverse reactions (black and gray arrows), and the equilibrium position ($Q = K$).

in concentrations such that $Q = K$ is reestablished). Prior work suggests that connecting the reaction equation to the progress of reaction is nontrivial. In one study, teachers and students incorrectly interpreted the meaning behind the language of "shifting" to one side of a reaction.[12] A classroom study that randomly assigned students to view online equilibrium lectures either with or without the progress of reaction diagrams found that viewing molecular diagrams of states of the reaction along the continuum improved student outcomes for low-performing students.[13] In a virtual lab activity, 50% of students misidentified the excess reactant remaining in a solution as a product of the reaction. These students were proficient at solving limiting reagent problems, suggesting that mastery of such problems does not imply qualitative understanding of the progress of reaction.[14]

Teach Equilibrium Problem Solving Using the M&M Strategy

In important application areas, such as acid–base and solubility chemistry, the equilibrium position of a reaction often lies far to the right or left of the progress of reaction of Figure 1. In such situations, a clear distinction exists between species that will have a large (majority) versus small (minority) concentration at equilibrium. Experts pay attention to K, the equilibrium constant, and take advantage of the distinction between reactions that will progress nearly to completion and those that will not. The M&M strategy is an instructional strategy for instilling this behavior in students. The M&M strategy breaks analysis of equilibrium systems into two phases (summarized here and expanded on below).

- In phase one, reactions with large K are identified and students are prompted to carry out a thought experiment in which these reactions run to completion. Chemical species that have nonzero concentrations after phase one are *majority* species. Chemical species whose concentrations are zero after phase one are *minority* species. As, in fact, the reaction does not progress all the way to completion, the minority species will be present with small but nonzero concentration at equilibrium.
- In phase two, laws of mass action ($Q = K$ at equilibrium) are used to determine the concentrations of the *minority* species.

Our first study suggests that experts use such a two-phase approach when analyzing equilibrium systems, although this is typically done implicitly. Making these two phases explicit to students, via the M&M strategy, has a number of potential advantages. The M&M strategy integrates qualitative reasoning ("What is present in large versus small concentrations in this solution?" and "Where along the progress of reaction will the system reach equilibrium?") with quantitative reasoning ("What are the values of the concentrations at equilibrium?"). When framed within the M&M strategy, quantitative problem solving can reinforce qualitative reasoning, and vice versa. The M&M strategy also provides an organizing structure for reasoning across applications of equilibrium, including acid–base and solubility chemistry. This structure can be introduced early in the course and used to frame further instruction, independent of a particular order of covered topics.

A single reaction with an intermediate value of K is a useful starting point for instruction in equilibrium. Quantitative reasoning typically centers around an Initial–Change–Equilibrium (ICE) table, shown below for a simple binding reaction with initial reactant concentrations of 1 M.

A	+	B	$\rightleftharpoons$	A:B	$K = 1$
1		1		0	initial
$-x$		$-x$		$+x$	change
$1 - x$		$1 - x$		x	equilibrium

The law of mass action then generates a second-order polynomial that can be solved for x. As further algebraic simplification is not possible, quantitative reasoning remains highly algebraic. Qualitative reasoning is also limited, consisting primarily of LeChatelier's principle. For systems involving multiple reactions, obtaining a quantitative solution becomes considerably more involved and is outside the scope of introductory courses. Thus, though a single reaction with intermediate K is a useful starting point for instruction in equilibrium, students need additional tools to be able to reason about more complex systems such as those of acid–base or solubility chemistry. Such additional forms of reasoning are available when K is large or small.

In current instruction, a common tool for reasoning about systems with a large or small value of K takes the form of a "small-x" approach. For a large K value, the reaction is first pushed all the way to completion (see "better start" in Figure 2). Displacement from this position is described with a variable x (see "change" and "equilibrium"). Because K is large, the displacement x, away from the better-start position, may be assumed to be very small (see "assume $x \ll 1.2 \times 10^{-6}$")

With the small-x assumption, the law of mass action is linear in x and easily solved to give $x = 4 \times 10^{-12}$. The assumption that $x \ll 1.2 \times 10^{-6}$ must be later checked and is accepted if it

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Small-*x* Approach

Protein	+ Drug	⇌ Protein:Drug	$K = 10^8$
1.2×10^{-6}	3.0×10^{-3}	0	*initial*
0	3.0×10^{-3}	1.2×10^{-6}	*better start*
$+x$	$+x$	$-x$	*change*
x	$3.0\times10^{-3} + x$	$1.2\times10^{-6} - x$	*equilibrium*
x	3.0×10^{-3}	1.2×10^{-6}	*assume* $x \ll 1.2\times10^{-6}$

M&M Strategy Phase 1: Determine the Majority Species

Protein	+ Drug	⇌ Protein:Drug	$K = 10^8$
1.2×10^{-6}	3.0×10^{-3}	0	*initial*
0	3.0×10^{-3}	1.2×10^{-6}	*assuming* $K = \infty$

M&M Strategy Phase 2: Determine the Minority Species

$$K = \frac{[\text{Protein:Drug}]}{[\text{Protein}][\text{Drug}]} \quad \frac{1.2\times10^{-6}}{[\text{Protein}]3.0\times10^{-3}}$$

Figure 2. Comparison of small-x and M&M approach.

applies to within some tolerance, typically taken as 5%.[15] Due to its algebraic character, this small-x approach may be perceived as simply a mathematical simplification. Assuming x is small converts a quadratic equation to a simpler linear equation.

Our assertion is that distinguishing majority from minority species is a central aspect of equilibrium reasoning. The goal of the M&M strategy is to bring this distinction to the foreground. The M&M strategy is mathematically equivalent to the small-x assumption. However, the instructional framing is substantially different.

The M&M strategy involves two phases (Figure 2). The first phase considers the magnitude of K to determine the identity and concentration of the majority species. This step is phrased as a thought experiment about what would happen if K were infinitely large, corresponding to a reaction that goes to completion.

At the end of phase 1, any species with nonzero concentrations are majority species, and the concentrations of these majority species are now known. Species with zero concentrations are minority species. As K is not really infinite, the reaction does not, in fact, progress to completion, and the concentrations of the minority species are not really zero, but rather need to be determined in phase 2.

Phase 2 of the M&M strategy uses the law of mass action, $K = Q$, to determine the concentrations of the minority species. From phase 1, the concentrations of the majority species are already known, and may be substituted into $K = Q$, which is easily solved for the concentration of the minority species, [Protein] = 4.0×10^{-12}. As the M&M strategy is applicable only when the minority species are present in smaller concentrations than the majority species, we check that this is indeed true. Here, the protein concentration is much smaller than the concentrations of the other species, and so the M&M strategy is applicable. (A 5% tolerance would be consistent with the small-x approach, though in our instruction, we use a 10% tolerance for estimations.)

For reactions with small K, phase 1 can pose the thought experiment "What would happen if K were not just small, but zero?" Alternatively, the reaction can be reversed to give a reaction with large K. We expect students to have familiarity with the fact that the reverse of an equilibrium reaction will have an equilibrium constant of $1/K$.

The M&M strategy is mathematically equivalent to the small-x approach. Step 1 of the M&M strategy is identical to finding the "better start" position of the small-x approach. Step 2 of the M&M strategy is equivalent to introducing the variable x and then ignoring it when it is added or subtracted from a majority species. Finally, the check that the minority species concentrations are small compared to the majority species concentrations is equivalent to the check of the assumption that x is small.

The advantage of the M&M strategy is the stronger coupling to qualitative reasoning regarding the position of equilibrium along the progress of reaction. The large K reaction is handled via a refinement of the limiting reagent approach. Limiting reagent reasoning applies when the reaction goes to completion. If the reaction instead goes nearly to completion, the only needed refinement is that the concentration of the limiting reagent is not zero but rather some small value.

EVIDENCE IN SUPPORT OF THE INSTRUCTIONAL RECOMMENDATIONS

Below, we outline two studies to support the instructional recommendations. Our research demonstrates that the progress of reaction is not obvious to novices and may require explicit instruction. Further, the M&M strategy may be easier to learn than current instructional approaches. In the first study, we use techniques from the field of cognitive science to determine whether and how novices and experts differ in equilibrium problem solving. In the second study, we compare 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 in Figure 3 as the basis of our research. We selected this problem because it meets three criteria. First, the equilibrium system has a strong ($K \gg 1$) forward reaction, which makes the problem a good candidate for an approximation strategy. Second, 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. All of our research was carried out with college undergraduates, graduate students, and experts that had already engaged in graded homework assignments that used letters (e.g., A, B, and C) to represent molecules.

> 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 is [A], [B] & [C] when the system reaches equilibrium?

Figure 3. Prompt used for the equilibrium problem in all studies.

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The Majority Minority (M&M) strategy aims to help students connect quantitative calculations with conceptual understanding of the meaning behind the calculations. We put forward the claims 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. The following sections describe two empirical studies to test these claims.

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

The goal of the expert/novice study was to identify how novices and experts differ in problem solving and whether experts use reasoning similar to the M&M strategy.

To investigate whether experts use M&M reasoning during equilibrium problem solving, we carried out a "think-aloud" study using verbal protocol analysis. Participants were asked to say everything they are thinking as they complete a task, and audio is recorded for subsequent analysis. Think-alouds are highly effective at revealing reasoning strategies and do not interfere with problem solving.[16−18]

Research comparing expert and novice problem solving has found 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.[11,19−22] In chemistry education, studies have similarly found student conceptions of equilibrium systems differ greatly from expert understandings.[23−26]

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 considering the range of possible states of the system and correctly applying the law of mass action using equilibrium values 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.

■ STUDY 1 METHOD

Participants

Five experts and ten novices had the option to be paid or receive course credit for participation in this study. Experts were three chemistry faculty members from Carnegie Mellon University who had recently taught introductory chemistry and two 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, described above, was the second question in a packet of five questions related to chemical equilibrium.

Design and Procedure

Participants were given instructions on verbal protocols using the script in Ericsson and Simon[17] 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.

A solution was coded as using the *progress of* reaction if the law of mass action was invoked using equilibrium values. Though the law of mass action ($K = Q$) applies only when the reaction has reached equilibrium, a common student error is to insert given, as opposed to equilibrium, concentrations into $K = Q$ while solving equilibrium problems. Students that fail to distinguish between these two very different positions on the progress of reaction are likely not considering the full range of possible states of the system. In the current problem, solvers must think through the progress of reaction, determine equilibrium values, and invoke the law of mass action, $K = [C]^2/[A]^3[B]^4$ *at equilibrium*. Students using a shallow strategy "solve" for the answer by instead inputting *initial* concentrations from the problem statement. For example, they set K equal to the initial concentrations and derive an erroneous value for the concentration of C.

A solution was coded as using *approximation* if the small-x approach or other two-phase approximation strategy was visible in problem solving. Both nonapproximate and approximate strategies for determining equilibrium concentrations are taught in introductory chemistry classes. The nonapproximate strategy introduces a variable x to account for the progress of reaction away from initial concentrations and would lead to difficult exponents in the law of mass action formula. As K is very large, the approximation strategy applies and leads to simpler math.

Finally, solutions were coded as correct if they found equilibrium concentrations for all three species, A, B, and C.

Analysis of Verbal Protocols

The verbal protocol analyses provide further evidence on whether solvers were invoking conceptual information related to the progress of the reaction. We hypothesized that experts would be more likely to explicitly describe the progress of reaction by referring to chemical reactions dynamically (e.g., revealing an understanding that the concentrations are changing along a continuum) and by referring to various states of the system (e.g., the initial state, the final state).

To determine whether novices and experts were thinking differently about the progress of reaction, 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", "at equilibrium", "at the beginning", and so forth. For example, "Initial concentrations are going to be reduced. So, your initial concentration is going to be 100 mL times 1.2 for A divided by total volume 150." We expect state-based comments to refer

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to the different "boxes" of an equilibrium system as depicted in Figure 1.

Utterances were coded as *reaction-based* if they used words such as "reacts" or "progresses." Words referring to reactions include "reacts with, goes to completion, loses all the B." 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." We expect reaction-based comments to refer to the movement between the "boxes" depicted in Figure 1.

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 fourth. *C* squared solving by multiplying 1.2 times 1.2 times 10 to the sixth" 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 coded as either state or reaction-based.

■ STUDY 1 RESULTS

Results from Written Problems

An analysis of problem solutions revealed that experts were more likely to integrate concepts with problem solving. All five of the experts correctly applied equilibrium values in the mass action formula, compared to less than half of the novices. In addition, experts were more likely to demonstrate M&M type reasoning as they more frequently used the approximation strategy during problem solving. All three professors used an approximation strategy, compared to no novices or graduate students. See Table 1 and Figure 4 for examples of written solutions.

Table 1. Number of Experts and Novices Who Used Equilibrium Values in the Mass Action[a] Formula and Used the Approximation Strategy

	Progress of Reaction (Equilibrium values in mass action formula)	Approximation strategy: No	Approximation strategy: Yes
Novice	No	5[b]	0
Novice	Yes	4	0
Expert	No	0	0
Expert	Yes	2	3

[a]$Q = K$. [b]One student did not invoke the mass action formula in problem solving. Data from this student is not reflected in the table above as the student took an incorrect approach that involved finding the number of moles of *A*, then multiplying that by the stoichiometric relationship ($2C/3A$) to "find" the number of moles of *C*.

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. Although no novices were able to use the approximation strategy, four of the ten were able to correctly apply equilibrium values when using the mass action formula. Further, though no experts mistakenly applied initial values to the mass action formula, only three of the five experts were able to use the approximation strategy. The results suggest a development of expertise because the two experts who failed to use the approximation strategy were the chemistry graduate students whereas the three experts who used the more appropriate approximation strategy were chemistry faculty. Overall, no novices and only two of the experts (that used the approximation strategy) arrived at the correct answer. The chemistry graduate students failed to find correct solutions using the nonapproximate approach and one professor made an arithmetic error that led to an incorrect final answer.

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 hypotheses were 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. Unpaired two-tailed t tests were performed. Overall, the mean number of comments was nearly identical for the experts ($M = 25.4$) and novices ($M = 25.1$), $t(1,13) = 0.04$, $p = 0.96$. The number of state-based and reaction-based comments of each type was tallied for each participant. The t test results revealed that experts made more *state-based* comments ($M = 4.6$) than novices ($M = 2.1$), $t(1,13) = 2.2$, $p < 0.05$, and experts made more *reaction-based* comments ($M = 3.0$) than novices ($M = 0.7$), $t(1,13) = 3.2$, $p < 0.01$. See Figure 5.

■ STUDY 1 DISCUSSION

Our study suggests 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 few statements that revealed 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.

As is typical with think-aloud studies, the number of participants in our study was small, so further research will be needed to establish the generalizability of these findings. However, as we found categorical differences and a developmental progress across levels of expertise, the results are suggestive that the M&M 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

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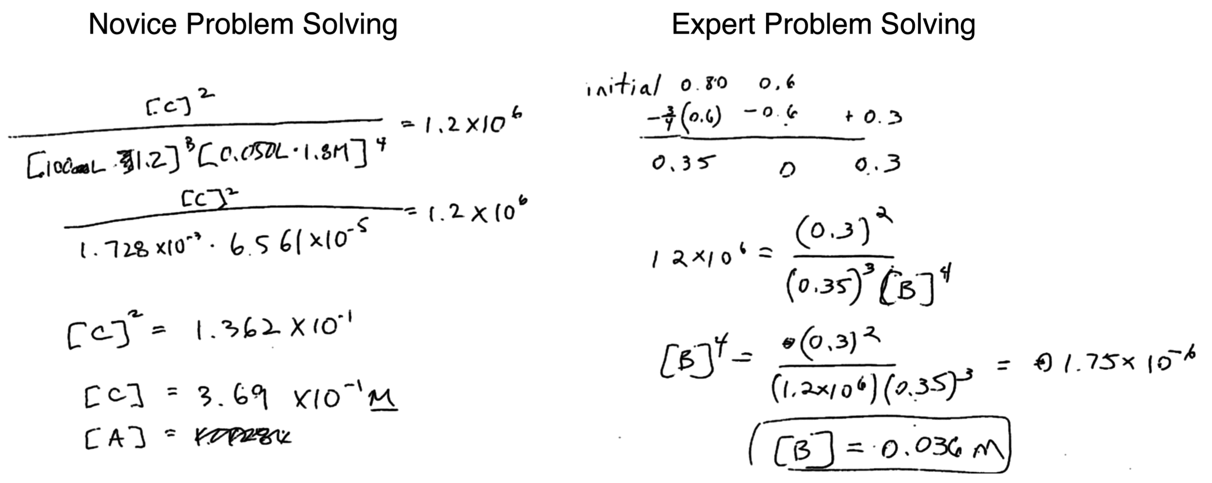

Figure 4. Left: Example of novice problem solving. Right: Example of expert problem solving. Notice that the novice invokes the mass action expression with nonequilibrium values and fails to use an approximation strategy, whereas the expert approximates the system reaching equilibrium and applies the mass action expression with equilibrium values.

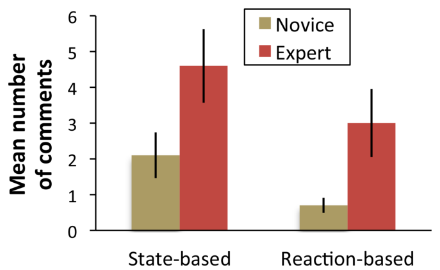

Figure 5. Comparison of state and reaction utterances for experts and novices.

solving was due to traditional equilibrium instruction that emphasized multistep procedures and instruction that was not grounded in conceptual understanding of the processes occurring in an equilibrium system.

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

In our second study, we compared the effects of instruction using the M&M strategy with instruction using the small-x approach to determine whether the M&M strategy would be readily learnable by students and lead to an increase in successful problem solving. We compared student problem solving performance over two different semesters of undergraduate chemistry. Data from the control semester were collected before the M&M strategy was developed. Control students were taught to solve equilibrium problems that involved a large K using the traditional, small-x approximation strategy.[15] In the treatment semester, students were taught to solve equilibrium problems using the M&M 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.

STUDY 2 METHODS

Participants

Exam data were collected from 310 students enrolled in second semester college chemistry (Modern Chemistry 2) courses at Carnegie Mellon in two different semesters. In the control semester, data were collected from 139 students (71 females and 68 males). In the treatment semester, data were collected from 171 students (81 females and 90 males). Students in both semesters were exposed to the same curriculum.

Procedure

In both semesters, the same instructor taught an approximation strategy for solving equilibrium problems during lecture and was reviewed in a subsequent lecture. Students in both semesters were taught to calculate the effects of dilution to identify starting concentrations. 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 M&M strategy. A tablet PC was used during class and worked examples were projected while the instructor explained the solution steps. In both semesters, lecture notes that captured all written information were available on the course Web site 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.

STUDY 2 RESULTS

Chi-square tests of independence were performed to examine the relation between being taught the M&M strategy and success on three measures of problem solving. The results demonstrated that students taught the M&M strategy were more likely to use equilibrium values in the mass action

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formula, were more likely to use the approximation strategy, and were more successful overall. Significantly more students in the M&M semester used equilibrium values in the mass action formula (80%) than students in the control semester (63%), $X^2(1, N = 310) = 10.88$, $p < 0.001$. Significantly more students in the M&M semester used an approximation strategy (92%) than students given the small-x instruction (24%), $X^2(1, N = 310) = 149.75$, $p < 0.001$. Finally, 50% of students given M&M instruction found all correct concentrations at equilibrium, compared with only 17% of students in the small-x condition, $X^2(1, N = 310) = 36.03$, $p < 0.001$. See Figure 6.

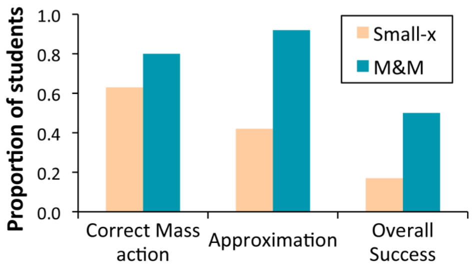

Figure 6. Comparison of semesters taught using the small-x approximation versus the M&M strategy. Left bars are the percentage of students using equilibrium values in the mass action formula, middle bars are the percentage using an approximation strategy, and right bars are the percentage obtaining correct concentrations.

■ STUDY 2 DISCUSSION

The results 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, a t test carried out with data from midterms does not support that claim. In fact, students in the control condition scored statistically significantly higher on the first midterm, taken prior to equilibrium instruction ($M = 88.2$), than students in the M&M group ($M = 78.1$), $p < .001$. Another hypothesis is that students in the M&M group may have been exposed to the exam item from the prior year. As the middle bars in Figure 4 indicate a large, qualitative difference in problem solving approach, it is unlikely that exposure to the question led to the results.

A number of factors may contribute to making the M&M strategy easier to learn than the small-x approach. In the small-x approach, the move to the better start position is motivated mathematically to support the algebraic simplifications arising from the assumption of small-x. Phase 1 of the M&M strategy replaces this with a thought experiment that focuses attention on the chemical consequences of having a large K. The thought experiment asks "What would happen if K were not just large, but infinite?" This question helps the transition to phase 2, when we ask "What are the consequences of K only being large, as opposed to infinite?" The small-x approach may obscure this chemical reasoning by introducing unneeded algebraic complexity. In particular, the various algebraic approximations (for example, x is ignored when added or subtracted from a large number but not when multiplied by a large number) are difficult. This may distract students from the key chemical idea that a reaction with large K lies to the far right of the progress of reaction. In addition, students may attach significance to the sequence of actions in the small-x approach, and misinterpret the reaction as proceeding to completion and then relaxing back to an equilibrium state. Phrasing the M&M strategy as a thought experiment may prevent this misinterpretation.

Although the M&M strategy and small-x approach are mathematically equivalent, our study provides preliminary evidence that the M&M strategy is considerably easier to learn and is more likely to result in successful problem solving.

■ SYSTEMS INVOLVING MULTIPLE REACTIONS

The studies presented here consider only the application of the M&M strategy to cases involving a single equilibrium reaction. The Supporting Information include instructional materials for systems, such as those of acid–base chemistry, where multiple reactions are present. The use of the M&M strategy to frame instruction for such systems has two potential advantages:

- M&M provides a single unifying approach to analysis of equilibrium systems. This is demonstrated in the Supporting Information by applying the M&M approach to a wide class of problems in acid–base and solubility chemistry.
- M&M exposes the reasoning involved at key decision points in the problem solving process, including especially selecting a chemical reaction to consider at a given point in the analysis. Exposing the reasoning used to select a reaction is especially important since the criteria for the selection change when one shifts from phase 1 to phase 2 of the analysis.

Studies of the impact of this suggested instructional approach on learning are left to future work.

■ CONCLUDING COMMENTS

This paper presents two instructional suggestions for equilibrium instruction, along with evidence supporting these suggestions.

The first suggestion is to provide explicit instruction on the progress of reaction. The verbal protocol study adds to prior work that suggests the connection between the reaction rule and the effects of this rule on a collection of molecules is not obvious for novices. Effective means of exposing students to the progress of reaction include visualizations that show the continuum of possible states of the equilibrium system. Recently, this strategy has also been used effectively in the ChemVLab+ project through activities that require students to drag and drop "states" into their place along the progress of reaction coordinates.[27−29]

The second suggestion is to use the M&M strategy to frame instruction. 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 during 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.

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Why is the M&M strategy more successful than the mathematically identical small-x approach? Our hypotheses is that explicitly connecting qualitative reasoning to problem solving steps was more successful as it allowed students to reason conceptually about what is happening in an equilibrium system rather than simply following a series of algebraic manipulations. Research in cognitive science resoundingly suggests that you "learn what you practice".[30,31] Expert chemists routinely reason qualitatively about chemical reactions and are fluent at integrating concepts with algorithmic manipulations. The M&M strategy provides a means to practice such reasoning. The strategy also applies to a wide range of chemical systems, such that repeated exposure across units may help students make conceptual connections both between concepts and procedures as well as across topics such as equilibrium, acid−base chemistry, and solubility chemistry.

For systems involving a single reaction, there is classroom evidence that the M&M strategy may be easier to learn than the mathematically equivalent small-x approximation. For systems involving multiple reactions, we hypothesize that learning benefits will result from using the M&M strategy to provide a single, consistent, approach to the analysis of equilibrium systems. Classroom studies testing the latter hypothesis are left to future work.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Use of the M&M strategy in acid−base and solubility chemistry is illustrated with a set of worked examples. In addition, the definition of "strong reaction" is refined from $K \gg 1$ to a criterion that works for dilute solutions. This material is available via the Internet at http://pubs.acs.org.

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Notes

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