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# Effectiveness of Inquiry-Based Lessons Using Particulate Level Models To Develop High School Students' Understanding of Conceptual Stoichiometry

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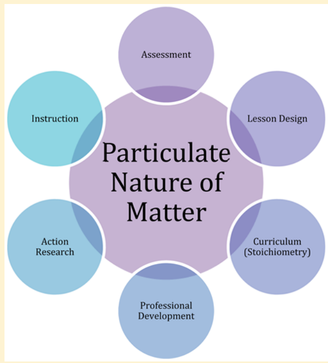
S *Supporting Information*

**ABSTRACT:** Students' inaccurate ideas about what is represented by chemical equations and concepts underlying stoichiometry are well documented; however, there are few classroom-ready instructional solutions to help students build scientifically accurate ideas about these topics central to learning chemistry. An intervention (two inquiry-based activities) was developed, piloted, and evaluated with common misconceptions in mind. The intervention was carried out in five sections of a high school chemistry class at a technical career campus, and pre/posttest data using a published instrument were collected to evaluate the intervention's effectiveness in building accurate stoichiometric concepts. Statistically significant growth with a large effect size occurred from pre to posttest demonstrating that the intervention improved conceptual understanding even though there were variations in the intervention delivery, as well as small differences detected between 11th and 12th grade student performance. The study, an action research project carried out by a teacher enrolled in a long-term professional development program, has implications for the value of rigorous materials design and evaluation framed by the chemistry education research literature. Study replication in other classroom contexts would be useful in further validating the learning outcomes of the activities. For practitioners, the activities studied here are free and available online for classroom use.




**KEYWORDS:** *General Public, High School/Introductory Chemistry, First-Year Undergraduate/General, Chemical Education Research, Curriculum, Inquiry-Based/Discover Learning, Misconceptions/Discrepant Events, Stoichiometry*

**FEATURE:** Chemical Education Research

## ■ INTRODUCTION

It should hardly be surprising that high school students around the world have serious misconceptions in chemistry.[1−5] Studies also reveal that college students have misconceptions as well.[6−9] Each of the studies previously cited specifically identified misconceptions having to do with stoichiometry such as limiting reactant concept, mole/mass ratio, and coefficient/subscript confusion. The studies make it apparent that there is serious confusion in the minds of students regarding stoichiometry and that better lessons are needed so teachers can help students build accurate understandings of this fundamental concept. Sanger published a study identifying students' misconceptions regarding balanced equations and stoichiometric ratios using particulate drawings.[9] It crystallizes what a high school teacher must know to promote learning: (a) students with a better understanding of subscripts and coefficients are more successful with stoichiometry problems; and (b) although students can use a balanced equation in a stoichiometric algorithm correctly, they do not understand the chemistry concepts that a balanced equation represents.[9] In other words, if a student can balance an equation, they might be able to establish molar ratios to solve stoichiometry problems, but there is no guarantee. And, even if a student can balance and correctly solve a stoichiometry problem, they may not understand the underlying concept or its application in practicing chemistry in a laboratory or in industry.

Chemistry teachers have assumed implicitly that being able to solve problems is equivalent to understanding molecular concepts.[7] Nurrenbern and Pickering's study concluded that there are important differences between the two goals, and achieving one does not imply achieving the other.[7] Sawrey challenged the findings in the above study by hypothesizing that the Nurrenbern and Pickering study used a very heterogeneous group and that higher achieving students would do well on both types of questions, and thus, the findings in the study would have no practical significance.[8] She concluded after administering the same assessment as Nurrenbern and Pickering[7] that higher achieving students had just as many problems with conceptual questions as low achieving students, and that there must be some way that teachers can simultaneously give attention to the qualitative and quantitative nature of chemistry so that one is not sacrificed for

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the other.[8] Recommendations for a more conceptual treatment of chemistry using particulate level ideas and representations has become more prevalent in secondary chemistry as evidenced by the new AP guidelines.[10] However, it is challenging for a teacher to translate the general recommendations for a conceptual focus into improved teaching practices or lessons that could advance student problem solving or conceptual understanding. These conclusions without practical examples leave gaps in the literature that this study hopes to fill by creating conceptually rich lessons related to stoichiometry and evaluating their impacts on high school student conceptual understanding.

## PURPOSE

Not only do high school students find stoichiometry difficult, but also many teachers find it difficult to teach.[11] The goal of this study is twofold: First, to design two lessons that could immediately be employed by teacher practitioners to facilitate better student conceptual understanding of stoichiometry concepts and also to assist teachers in teaching stoichiometry without having to develop effective conceptual lessons for themselves; and second, to evaluate the effectiveness of the lessons with respect to student understanding. Researchers assert that the use of inquiry-based methods, as well as developing and using particulate models, planning, and carrying out investigations; and using mathematics and computational thinking, as well as using sound instructional strategies such as the use of analogies and metaphors, predict-observe-explain sequences, talk moves, and thought experiments,[12] will increase student understanding of the following stoichiometry concepts/tasks: limiting reactants, subscript/coefficient meaning, applying a balanced chemical equation to the solving of a molar ratio problem, and mole/ratio proportional reasoning.[1,3−6,9,13−15]

The research question that guided this action research study is: How will inquiry-based lessons using particulate level models affect high school student understanding of conceptual stoichiometry?

## METHODS

### Research Design

This study aimed to investigate the effectiveness of two inquiry-based, particulate level lessons in improving students' conceptual understanding of stoichiometry. With the use of a quasi-experimental, quantitative study with a one-group pretest−posttest design,[16] the intervention engaged students in inquiry-based activities with various particulate level representations of matter and asked students to predict and test the outcome of a wet lab. The two intervention lessons were implemented during the later half of the second semester of the school year. The lessons implemented in the study were designed by the first author and was piloted and revised by a team of chemistry educators as part of the Miami University's Target Inquiry teacher professional development program.[17] In the pilot, nine other secondary teachers along with two chemistry education researchers and a graduate student carried out the lesson playing the role of students. After the lesson, an extensive debriefing informed improvements to the figures, questioning strategies, and overall organization.

The classroom lessons were designed to be implemented at the beginning of a traditional general chemistry stoichiometry unit. The lessons aimed to provide students with a strong conceptual understanding of molar ratios, limiting reactants, and molar mass relationships in stoichiometry.

### Setting and Sample

The intervention lessons were implemented in five high school introductory general chemistry sections at a career technical high school located in the Midwest United States. The school consists of approximately 650 students who attend their 11th and 12th grade years of high school. Students attend the entire school day and receive career technical instruction for half of the day and academic instruction in science, social studies, math, and English the other half of the day. Academic credits are transferred to the students' home school and used to meet state graduation requirements. The goals of the school are to promote career path readiness and college preparedness. Academic classes are attended every day and last for 43 min each. The first author was the instructor for all five chemistry sections that were studied. Senior students have the opportunity to enter their job placement and drop academic classes that are not required for graduation. Data were not compared to a control group or established norms. The students in three sections consisted exclusively of second year career-tech (12th grade) students, $N = 38$. The sample in two sections consisted exclusively of first year career-tech (11th grade) students, $N = 26$. The participants were 16−19 years old, predominantly Caucasian and working class. The intervention lessons were implemented over seven consecutive instructional periods, during the 10th and 11th week of the second semester of the 2014−2015 school year.

### Intervention and Evaluation Overview

Two intervention lessons were implemented over the course of seven school days. The lessons are titled *Balancing in a Particulate Way* (BPW) and *Not Leftovers Again* (NLA); BPW was the first lesson and NLA was taught second. The pretest was administered at the end of the period prior to the first lesson being taught. On the seventh consecutive day of school following the introduction BPW, the posttest was administered. The seventh day of the intervention fell on the last day of school before spring break. The first author thought it prudent to posttest the students before spring break. Due to this unfortunate scheduling of the curriculum, only the 12th graders received the complete intervention of both lessons prior to the posttest. Those students were posttested immediately following the conclusion of NLA.

During the course of lesson one, the juniors requested more teacher facilitation, as they were not comfortable that they understood the activity. A short assessment of understanding was given after lesson one. The juniors expressed frustration with the assessment and asked for help; many students said they, "did not know what to do". The instructor immediately collected the assessments and reviewed key parts of lesson one pertaining to a photosynthesis equation. These students also requested more explanation of the concepts of stoichiometry using the particulate diagrams. The assessment was given 2 days later. The 12th grade sections of chemistry expressed no verbal frustration when the assessment was administered. Due to the slower pace of lesson one, the 11th graders did not get to complete lesson two of the intervention prior to the administration of the posttest. All students $N = 64$ included in this study completed lesson one, a formative assessment following lesson one (accessible on the Target Inquiry Web site http://targetinquirymu.org), a single page molar ratio work-


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sheet, and the prelab/engagement section of lesson two. Table 1, shows interventions for 11th and 12th graders.

**Table 1. Intervention Delivery and Data Collection Schedule for Both Student Groups**

| Students | Pretest Administered | Activity 1: BPW | Activity 2: NLA |
|---|---|---|---|
| Juniors (11th grade) | Day before BPW | 6 class periods; complete activity | 1 class period; prelab only |
| Seniors (12th grade) | Day before BPW | 4 class periods; complete activity | 3 class periods; complete activity |

## Description of Intervention Lessons

The teacher guide and student guide for lesson one, as well as an assessment for the lesson, *Balancing in a Particulate Way* are available at http://targetinquirymu.org. The lesson was created with student misconceptions in stoichiometry pertaining to poor understanding of chemical formulas and equations in mind. Students appear not to understand the difference between the coefficient and the subscript when posed conceptual questions.[15] Students who can solve mathematical problems often have difficulty answering particulate-level conceptual problems addressing the same topics.[7] These well-documented, inaccurate student ideas helped to shape the types of experiences that should help students construct accurate ideas.

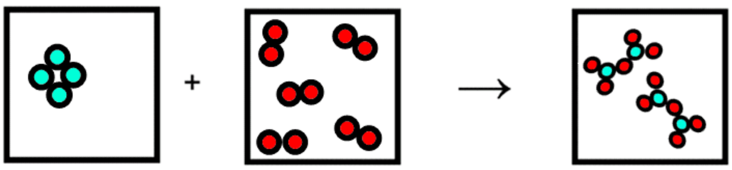
To help students gain a conceptual understanding of equation balancing, the activity uses particulate models and poses questions that confront students' common incorrect ideas. BPW is designed to facilitate student understanding of particulate and symbolic stoichiometry. It has also been suggested that the use of multiple representations in chemistry can dispel student misconceptions.[6] Symbolic equations and particulate drawings were used as multiple representations of the same chemical reactions. The activity uses 10 different reactions of covalent compounds and represents them symbolically as well with particulate-level models. Students are asked a series of questions about each reaction that leads them to conclusions that reactions happen according to whole number ratios. Students are asked to transfer knowledge between the two representations of the reactions using inquiry-based questions.

Students were presented with the lesson which was a packet of the equations and diagrams discussed above and asked to work in groups as they progressed through each chemical reaction. The instructor facilitated learning by walking around the room and addressing student questions as needed. Also, at various check points students had to present their answers to the teacher before they were allowed to progress further in the lesson. No direct instruction on equation balancing or limiting/excess reactans was used during the lesson. Students were asked to define limiting and excess reactants according to the examples given in the lesson. They also identified molar ratios and excess and limiting reactants using examples of particulate-level models of reactions. The lesson employed the learning cycle framework[18−20] in which students built knowledge about balancing and conservation from exploring particulate and symbolic models and inventing concepts guided by scaffolded questions. An example of reaction and follow-up questions from BPW ois presented in Figure 1.

Lesson two of the intervention *Not Leftovers Again*, also available at http://targetinquirymu.org, was designed to help students connect the symbolic, algorithmic, and macroscopic elements of stoichiometry. NLA specifically targets misconceptions associated with stoichiometry such as students' assumptions that chemicals react on an equal mole basis, mole and mass ratios are equivalent, and molar masses are the same as actual masses.[21] Furthermore, when students need to take into account proportions in a chemical change, they think

The diagrams below represent a particulate drawing of a balanced chemical equation of phosphorus and oxygen reacting.

Use the following key to interpret the diagram: phosphorus oxygen

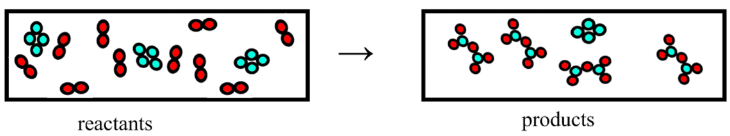


A) Using the particulate drawing above write a balanced symbolic equation of the reaction of phosphorus and oxygen.

B) How does the above particulate drawing assist you in deriving a balanced symbolic chemical equation?

C) Refer to the diagram below to answer the following questions.

Use the following key to interpret the diagram: phosphorus oxygen




A student wrote the following chemical equation to represent the reaction in the diagram above:

$3P_4 + 10O_2 \rightarrow 4P_2O_5 + P_4$. Explain in as much detail as possible why the student's chemical equation is inaccurate.

**Figure 1.** Excerpts of the lesson, *Balancing in a Particulate Way*.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PREDICTION

$Al(s) + CuCl_2(aq) \rightarrow Cu(s) + AlCl_3(aq)$

Circle the ratio below that you think will result in the complete use of reactants in the chemical reaction above with no visible leftover aluminum.

| Choice | Al:$CuCl_2$ ratio | Amount of Al needed | Amount of $CuCl_2$ needed |
|---|---|---|---|
| A | 1:1 mass ratio | 0.5 g | |
| B | 1:1 mole ratio | 0.5 g | |
| C | 2:1 mass ratio | 0.5 g | |
| D | 2:1 mole ratio | 0.5 g | |
| E | 2:3 mass ratio | 0.5 g | |
| F | 2:3 mole ratio | 0.5 g | |

Explain the reason for your choice.

DATA AND OBSERVATIONS

| | Ratio of Al:$CuCl_2$ | Amount of aluminum needed | Amount of $CuCl_2$ calculated | Mass of $CuCl_2$ Used | Visible aluminum present Y/N |
|---|---|---|---|---|---|
| A | 1:1 mass | 0.5 g | | | |
| B | 1:1 mole | 0.5 g | | | |

**Figure 2.** Excerpts from the lesson *Not Leftovers Again!* showing how the prediction and wet lab phases work together.

of appropriate volumes or appropriate masses and do not understand that the quantities to be taken into account are amounts of matter, which implies the use of the mole concept.[5]

This lesson helps students establish the concepts in stoichiometry prior to addressing traditional stoichiometric mathematical problems[15] with the hope of sidelining common misconceptions that seem to arise from a purely mathematical approach. It has also been suggested that providing students with multiple representations of a chemical concepts will alleviate the above misconceptions.[14] This method was employed in the lesson by connecting the symbolic balanced equation of a reaction to the actual reaction happening on a macroscopic scale and presenting students with analogies.[22] The reaction studied in this lesson is between aluminum and copper(II) chloride.

The prelab/engagement activity of NLA used the analogy of baking to introduce the idea that chemical reactions are similar to recipes. The analogy was used to facilitate comfort among the students with the idea of proportions. Students are asked to apply the ideas of doubling a recipe to increasing amount of products. The prelab/engagement activity was presented to the students and completed in a teacher-led discussion. At the conclusion of the activity, students were asked to make predictions.

During the actual lab activity, students are asked to predict which ratio of the reactants will lead to the use of all reactants and then asked to perform an experiment in the lab to test their prediction. The students are required to calculate all amounts of copper(II) chloride needed to test all proposed ratios in the lab. At the conclusion of the lab, students are asked a series of analysis questions that have them discover that the correct ratio of reactants is based on a molar ratio derived from the balanced chemical equation. The activity is designed such that many students will make incorrect predictions and be dissatisfied with their explanations, making the correct scientific explanation more plausible. Additionally, the literature emphasizes the importance of laboratory experiments in teaching for conceptual change in chemistry, and this lesson provides such an experience.[1] Finally, NLA is a lesson that bridges the conceptual to the mathematical by asking the students to use proportional reasoning skills when calculating the amounts of copper(II) chloride needed to test each ratio. An excerpt of NLA can be found in Figure 2.

## Instruments and Data Collection

In determining the effectiveness of the lessons in improving students' conceptual understanding of stoichiometry, a published conceptual stoichiometry test (CST)[15] was used. The instrument consists of six multiple choice items and four constructed response items. Two changes were made to the multiple choice items by the instructor (first author). Item five on the original CST asks students to determine how many million oxygen atoms would be needed to react completely with one million sugar molecules, using a the balanced chemical equation for cellular respiration. Because oxygen does not exist as individual atoms, the item was changed on the pretest and posttest used in this study to ask, "how many million oxygen molecules would be needed to react completely with one million sugar molecules?" Also, the original CST gave students five response choices; the instructor reduced the number of choices to four. With the use of data from Wood and Breyfogle,[15] the least frequently selected distractor for each question was omitted. The multiple choice questions used in this study are in the Supporting Information.

Students participating in the study were given the CST as a pretest and a posttest to measure any changes in their conceptual understanding of stoichiometry. Parental consent and student assent was obtained according to the approval granted by the Human Research Review Committee at Miami University at the beginning of the first semester. Only data collected from those students who turned in signed consent forms were used in this study. All students who were absent for either the pretest or posttest had their scores excluded from the study. Upon the completion of the posttest, students' pre- and posttest were matched, and both tests were graded simultaneously. This was done to avoid any unintentional discussion of the pretest while the students were engaged in the intervention lessons. Students were not allowed to keep the pretest nor were they allowed to discuss the test content during the intervention.



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### Data Analysis

Descriptive pre- and posttest results for all students were compared. A repeated-measures analysis of variance (ANOVA) was conducted to determine if differences between pre- and posttest scores were apparent as well as differences in growth from pre to post for 11th and 12th graders. Since there was no control or comparison group, results were compared to published outcomes for a common conceptual stoichiometry item to better situate this sample's findings in the larger chemistry student population.

The limitations in implementation and timing of testing were taken into consideration in the analysis. Although these are nonideal from a research design perspective, the limitations are representative of the daily goings-on in high school classrooms and lend authenticity to the evaluation of instructional materials for secondary settings.

## ■ RESULTS AND DISCUSSION

Since growth from pretest to posttest was an explicit goal of the intervention development, it was useful to examine posttest versus pretest scores of all the students as shown in Figure 3.

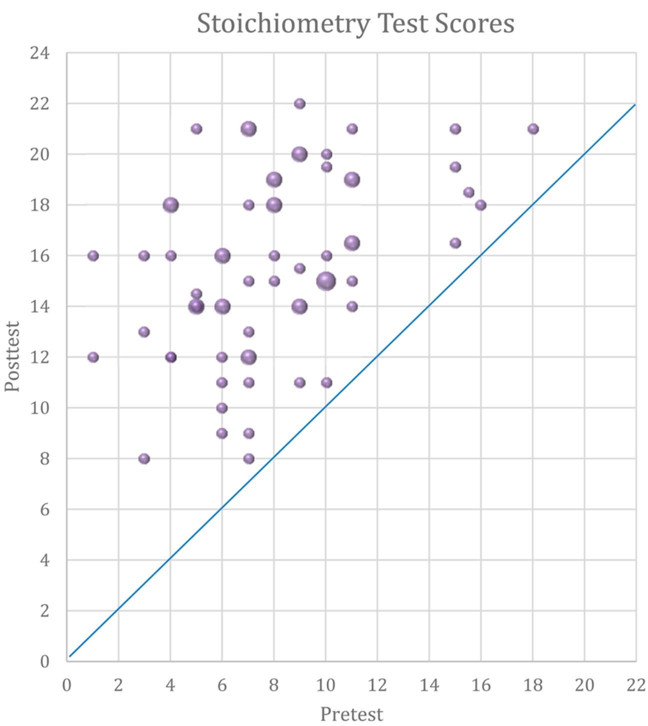


**Figure 3.** Posttest versus pretest scores (max score = 22) with a line indicating the boundary between positive and negative growth due to the intervention. Small bubbles represent one student, medium bubbles represent two students, and large bubbles represent three students.

Figure 3 represents the distribution of scores for the entire sample and demonstrates that all students improved to some extent due to the intervention since the bubbles appear above the $y = x$ line. (The extent is evaluated with an ANOVA below.) Table 2 shows scores (means and standard deviations) on the evaluation instrument from before (pre) and after (post) the intervention for the two student groups under study. Because the intervention delivery and instructional components were different for the junior and senior student groups, we found it essential to consider changes in student learning as measured by the conceptual test for each of the two groups together and separately. Since the sample is small, an Anderson Darling test was conducted to see if the distributions of pretest, posttest, and gain (post−pre) scores were normal. Although the distribution of pretest scores was significantly different from normal, the distribution of posttest and gain scores were not significantly different from normal. Furthermore, ANOVA can yield reasonably accurate $p$-values even when the normality assumption is violated, and a moderate sample size is 30; the sample size should be large enough to yield fairly accurate $p$-values.[23] Lastly, since the gain scores are multivariately normally distributed in the sample, it supports the use of an ANOVA.

**Table 2. Descriptive Statistics of Evaluation (Pre and Post) for Juniors and Seniors**

| Students | Pretest Mean (SD) Max = 22 | Posttest (SD) Max = 22 | *N* |
|---|---|---|---|
| Juniors | 7.7 (3.6) | 16.5 (2.9) | 26 |
| Seniors | 8.1 (3.7) | 15.0 (4.0) | 38 |
| Total | 8.0 (3.5) | 15.6 (3.6) | 64 |

To determine if conceptual understanding changed due to the intervention for both classes (pre to post) and if there was a difference in how juniors and seniors changed, we conducted a two-way repeated-measures ANOVA using SPSS 22. The dependent variable was test score ranging from 0 to 22. The repeated measure (within-subjects factor) was time with two levels (pre and post intervention). The between-subjects variable was grade with two levels (junior and senior). The time main effect and grade $x$ time interaction effect were tested using the multivariate criterion of Wilk's lambda (Λ). The time main effect was significant, $\Lambda = 0.215$, $F(1, 62) = 272.9$, $p \leq 0.001$, with a large effect size ($\eta_p = 0.815$). This showed that instruction across all students significantly improved conceptual understanding. Almost 82% of variance in test scores can be explained by when the students took the test, before or after the intervention. Changing the focus on differential growth by grade, the grade $x$ time interaction effect was also significant, $\Lambda = 0.933$, $F(2, 62) = 4.35$, $p = 0.039$, with a small effect size ($\eta_p = 0.067$). Figure 4 demonstrates that the juniors made slightly greater gains than the seniors due to the intervention. Interestingly, the juniors received the same number of days of instruction as the seniors but focused on less material.

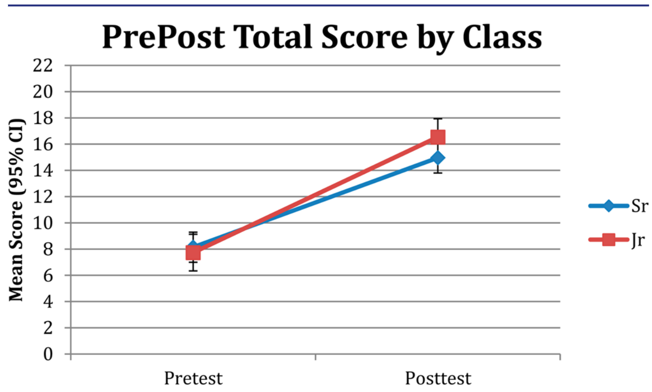


**Figure 4.** ANOVA plot demonstrating the time (pre/post) $x$ grade interaction and the slightly greater growth from intervention for the juniors over the seniors. It is important to note that this is a fairly small difference and demonstrates how the interventions caused very similar outcomes in student learning although they were delivered differently.


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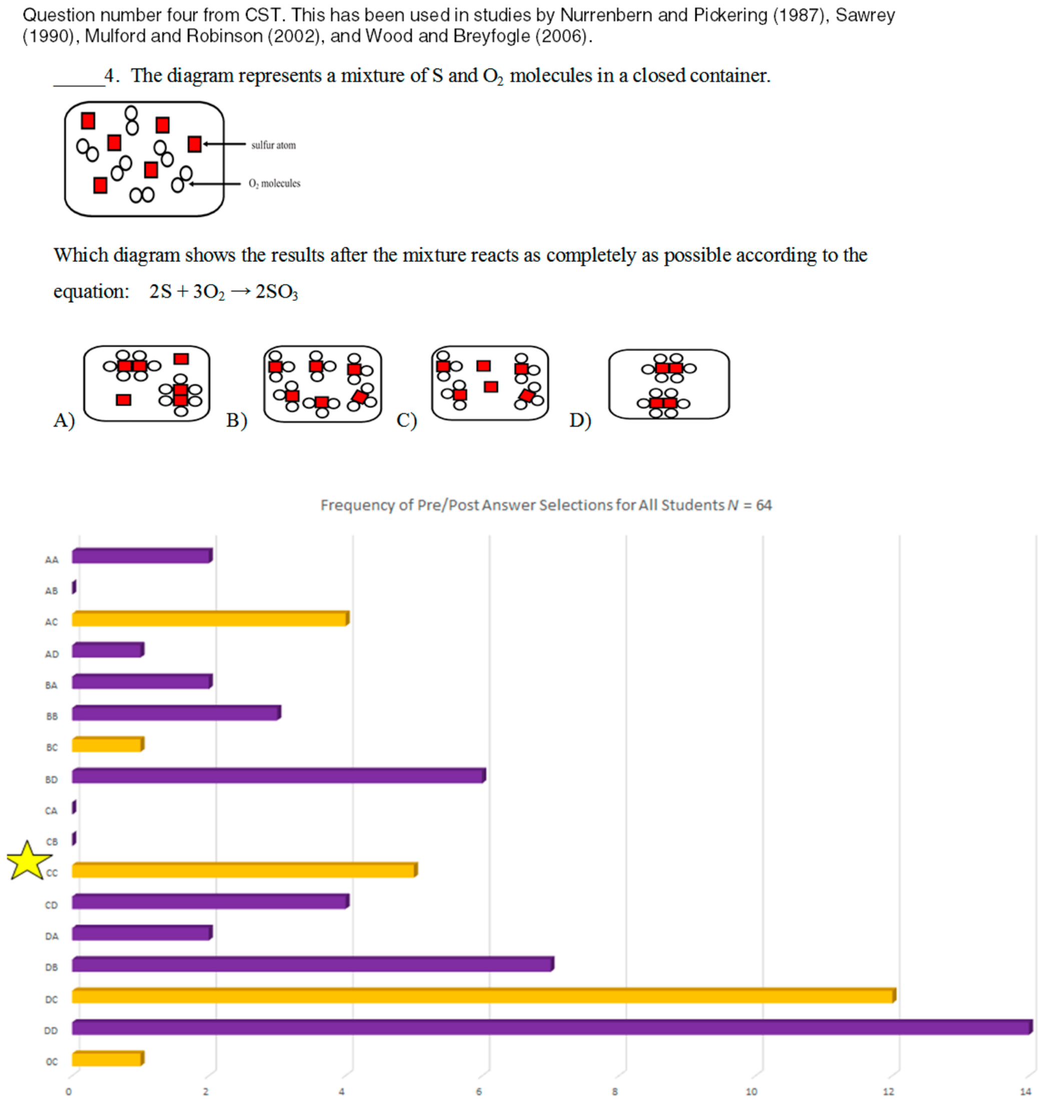


**Figure 5.** Conceptual stoichiometry item (top) and frequency of answers selected (bottom). The first item in the pair shown in the frequency graph is the pretest response and the second item is the posttest response. The correct answer is C.

The normality assumption was discussed above. With respect to the other assumptions underlying the ANOVA, the independence assumption is met because the students were tested individually during both administrations. It is possible that students' development of conceptual understanding was influenced by peers. Lastly, the Lavene's test was not significant, indicating that the variances of the scores from both time points in the study were similar.

The most difficult multiple choice question on the CST is item 4 (Figure 5, top). It is of particular interest because it has been used in several studies and many authors have reported results.[6−8,15] Students in this study ($N$ = 64) went from 14.1% choosing the correct answer to 35.9% choosing the correct answer on the posttest. In comparison, 11% of students answered correctly on the pretest and 20% answered correctly on the posttest in the Mulford and Robinson (2002) study. Mulford and Robinson's study[6] was based on measuring changes in conceptual understanding over the course of a college semester chemistry class, and no attempt was made to address misconceptions among those students. It is encouraging that the growth on this particular question increased by 21.8% vs 9% in the Mulford and Robinson study. Wood and Breyfogle[15] had similar results to Mulford and Robinson[6] regarding item four. We find it validating that the treatments used to increase conceptual understanding did in fact have a positive effect, especially when compared to studies in which different treatments or no treatments were used.

Figure 5, bottom, shows the frequency of pretest to posttest choices for question four. The $y$-axis shows all of the possible pretest−posttest combinations of answer choices with the first of the pair for the pretest and the second for the posttest. An examination of Figure 5 shows that the most persistent misconception is choice D, since the majority of students who did not change their answer from the lessons is the longest bar (DD). These results are consistent with the Mulford and Robinson study,[6] as 60% of the students on the pretest and 50% of students on the posttest chose a representation of $S_2O_6$. Most of the students in this study who chose the correct answer on the posttest chose D on the pretest. What is encouraging is that of the 26 students who picked D on the pretest, 14 (46%) of them changed their ideas after the lessons.

While the students as a group significantly increased their understanding of stoichiometry (Figure 4), the results indicated that the 11th grade juniors did significantly better than the 12th


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grade seniors although the effect size is small ($\eta_p = 0.067$). This is somewhat counterintuitive because the seniors received more intervention by completing both lessons prior to completing the posttest and were second year students in the school. Also, as was previously mentioned, the juniors requested more teacher explanation on how to proceed through BPW and the summative assessment that followed. This phenomenon has been documented in the literature. It has been suggested that seniors may be more reluctant to change their learning methods as they are close to completing school.[24] Perhaps the very reason the juniors achieved slightly higher scores is that they did ask for more explanation and proceeded at a slower pace. In essence, the juniors as a collective group knew what they did not understand and were motivated to ask for help to achieve a better understanding, whereas the seniors asked for less facilitation because they were not metacognitively aware that they did not understand what they did not understand. Alternatively, the first lesson, on which the juniors spent more time, could better prepare students for the posttest than the second lesson.

Another possible explanation for the phenomenon is that the seniors were experienced students in the two-year school, and the posttest took place immediately prior to spring break, during the final weeks of the school year. All the seniors were aware of their current GPA and the necessity (or lack) of a passing grade in the fourth quarter of chemistry to achieve graduation. Many had already obtained their science credits for graduation and did not have to pass the chemistry class to graduate. Also, many seniors were placed in jobs and had earned their career certification credentials. As such, they were perhaps not academically motivated. It is well documented that a lack of student motivation can have a great effect on student achievement in chemistry.[25,26] By comparison, the juniors were novice students in the career technical school, who had not yet earned career certification credentials, and were not in a position to go on job placement at this point in their enrollment. Also, the junior students were required to pass the chemistry class to obtain their third science credit for graduation. This could have led to a stronger group engagement and willingness to express concern when many of them were not comfortable with the assessment given at the conclusion of BPW.

## CONCLUSIONS AND IMPLICATIONS

A plethora of studies have been published citing high school and college student misconceptions in conceptual stoichiometry. Very few studies can be found that have validated classroom-ready lessons that can alleviate student misconceptions. While some lessons have been published on increasing student conceptual understanding of stoichiometry, they have not been tested and validated using quantitative data.[26−28] Other lessons have been quantitatively tested, but the lessons themselves were not published and/or available to teachers.[15,30] Due to the lack of published, validated, teacher-ready lessons related to conceptual stiochiometry, this study was performed with the intention of creating two lessons and evaluating their effect on student understanding of conceptual stoichiometry. In referencing the data presented above on student performance, it is apparent that the two lessons designed for this study had a profound positive effect on student understanding of conceptual stoichiometry.

The two lessons in this study were created during a 2.5-year professional development program Target Inquiry (TI) at Miami University. In the program, teachers learn how to design and use inquiry-based teaching methods, particulate models, wet lab investigations, and mathematical and computational thinking, all of which have been suggested and valid instruction tools for conceptual leaning.[12] However, not all teachers have the resources and availability to engage in long-term, content-centered, inquiry-focused professional development. As such, making high quality materials freely available to teachers is a primary goal of the TI project. The ultimate goal of this study was to create lessons that would assist educators in helping students attain conceptual understanding of stoichiometry without having to develop the lessons themselves and use them with efficacy. This study played a significant role in evaluating and evidencing lesson quality.

We hope that these lessons be used in tandem with algorithmic lessons in stoichiometry, particularly to introduce the stoichiometry concept. The first author can only offer anecdotal evidence that these lessons helped students better understand algorithmic stoichiometry. However, it was the first authors' difficulty in teaching algorithmic stoichiometry that led to the inception of these conceptual lessons. Future work could be to study the effect of these two lessons on the success of student understanding of algorithmic stoichiometry such as three-step mass-to-mass calculations. It would also be interesting to study these lessons' effect on students in a college general chemistry class, as multiple studies have shown that misconceptions exist in that population of these students as well.[6,8,9,13−15,29,30] The lessons could also be evaluated using a traditional academic group of high school students such as those in an honors or dual credit chemistry class. Studies have been shown that traditionally high achieving students in chemistry[8] have just as many misconceptions in conceptual stoichiometry as those who are lower achieving, yet educators intuit that their students do not have these misconceptions. The students in this study were a very nontraditional group of career technical high school students. An educator in an honors chemistry class might feel that these lessons are not challenging enough for honors students and thus not use the lessons in their curriculum, even though student misconceptions exist in such populations.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b01010.

Multiple choice and constructed response stoichiometry items used for the pre- and posttest in the study adapted from Wood and Breyfogle, 2006 (PDF, DOCX)

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### Notes

The authors declare no competing financial interest.

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