As the boundaries that separate various disciplines of Science, Technology, Engineering, and Mathematics (STEM) continue to blur, emerging technologies require students to utilize problem-solving skills that are transferable among the disciplines. A student’s formal reasoning ability has been identified as a reliable indicator of their success in STEM-based disciplines. (Tobin & Capie, 1981; Cantu & Herron, 1978; Goodstein & Howe, 1978) Trifone suggests the Test of Logical Thinking can be used as a tool for placing science students into level-appropriate classes based on their reasoning aptitude. (1987) As students matriculate through secondary and college level science courses, it is key that course learning-objectives and problem-solving methods bolster their reasoning abilities and growth as critical thinkers.

Ratio and proportions (RAP) is a topic that adolescent students experience during their personal maturation (Heller, et al., 1989) (i.e. unit pricing, gas mileage, and average speed) and in their academic course work (algebra and calculus classes). Formally, a proportion is a statement of equality of two ratios (such as \(a/b = c/d\)). In the physical sciences, a fundamental understanding of proportional reasoning extends to density, acceleration, stoichiometry, concentration, power, efficiency, gas laws and so on. Problem-solving strategies and the extent to which textbooks incorporate student exercises, have evolved over the years. (Jensen, 2003) For example, in “Chemistry”, Linus and Peter Pauling (1947), solved stoichiometric mass problems using proportional reasoning. Pauling writes, “The way to work a mass-relation problem is to think about the problem, in terms of atoms and molecules, and then decide how to carry out the calculations.” (p. 89) This approach encourages students to be critical thinkers and devise modes of solving stoichiometric problems, without rote memorization. (Canagaratna,
During worked examples of stoichiometric calculations, Pauling limits the use of units until the final answer.

Texts that were first published in the mid 1960’s, began emphasizing how chemical formulae and balanced equations describe quantitative relationships on both the particle level (atomic scale) and on the phenomenological level (lab scale). (Schmidt, 1997) In the text Chemistry: Principles and Applications, written by Sienko and Plane (1966), the authors write, “A chemical equation is valuable from two standpoints. It gives information on an atomic scale (i.e., atoms and formula-units that are visible) and also on a laboratory scale (i.e., moles of atoms and moles of formula-units that correspond to visible, convenient weights of chemicals).” (p. 44) The authors continue, stating that the conversion of atoms and/or molecules to moles can lead to a practical application in the laboratory setting because the total mass of reactants is equal to the total mass of the products based on the balanced equations (indication of the Law of Conservation of Mass). In the text College Chemistry, Mahan proposed that the ‘proportional method’ and the ‘mole method’ are equivalent. (p. 26) “Since stoichiometric coefficients in a chemical equation are generally small integers, the number of moles of one substance can be found from the number of moles of another by a simple multiplication involving the ratio of small integers.” (p. 27)

Texts published as early as 1978 (based on our cursory analysis), abandon the aspect of proportional reasoning and encourage students to solve mass relationship problems with interconnected conversions on a single line. A list of fifteen texts that use DA as the primary problem-solving method when solving stoichiometry and mass related problems are listed in a communication of Cook and Cook. (2005) In the opening chapter of the 6th edition of Chemistry by McMurry and Faye (2011), in the section “Calculations: Converting from one unit to another”, the authors states, “The key to the dimensional-analysis method of problem solving is that units are treated like numbers and can thus be multiplied and divided just as numbers can. The idea when solving a problem is to set up an equation so that unwanted units cancel, leaving only the desired units.”10 The reader is then properly cautioned that, “The main drawback to using the dimension-analysis method is it’s easy to get the right answer without understanding what you’re doing.” (p. 23)

We believe the results of this study demonstrate the value of incorporating Pauling’s method of proportional reasoning in introductory chemistry. Solving problems with RAP enables students to gain a deeper understanding of how mass values are proportionally related to the balanced equation through the mole. Students who have the ability to critically think and utilize RAP to solve stoichiometric problems demonstrate that this ability leads to a greater understanding of general chemistry.

Methods

At a public Hispanic Serving Institution (HSI) in the western United States with a student population of approximately 22,000, student work was examined to explore the effect of using proportional reasoning problem-solving methods in general chemistry. This study
involved three sections (173 students total) of the first quarter (ten weeks) of an introductory general chemistry course. Students enrolled in this course are predominantly majors from the Colleges of Science, Engineering, and Agriculture. The three course sections involved in this study had the same instructor, textbook, and online homework suite available through the text publisher. Enrolled students completed weekly homework assignments, quizzes, two exams, a final exam, and participated in class using an interactive response system. It should be noted, the textbook and online homework suite support solving examples of stoichiometric calculations using DA, rather than RAP.

**Table 1. Free Response Topics by Exam**

<table>
<thead>
<tr>
<th>Exam I</th>
<th>Avogadro’s number, the mole, stoichiometry (limiting and excess reagents), percent yield, percent mass, and isotopic abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam II</td>
<td>Combustion analysis, empirical gas laws, density and molar mass of unknown gases (related to the Ideal Gas Law), solution stoichiometry (including the molarity of solutions and volume of gases), writing of net ionic aqueous equations.</td>
</tr>
<tr>
<td>Final Exam</td>
<td>Additional topics include an emphasis on quantum mechanics, ground state electron configurations, orbital-filling diagrams, covalent bonding, molecular structure, resonance, and formal charge.</td>
</tr>
</tbody>
</table>

Exams I and II feature nine broad multiple-choice questions, ten short written/fill-in-the-blank responses, and five free-response questions that require students to show all their supporting work and calculations. The comprehensive final exam is similar to the other exams and includes additional topics detailed in Table 1. Proportional reasoning strategies can be used to solve a healthy portion of each exam. The exams used among the various sections were comparable and include embedded questions to ensure valid comparisons.
This protocol specifically examined the effect of proportional reasoning in the performance and understanding of students in general chemistry and was approved by the campus IRB. The investigators identified students as using RAP or DA from their written answers to embedded (free response) mass relationship problems that required calculations during Exam I. This identification facilitated the exploration of whether a student’s problem-solving technique had an influence on their course performance and subject comprehension. Students who did not complete the course or submit an answer to the identifying imbedded exam questions were excluded from the analysis of this study.

The treatment population (n=98) received instruction during lecture that emphasized problem-solving strategies using RAP. A 60-minute, volunteer recitation session (during weeks 2-4 of the course) was offered that focused on solving stoichiometric problems to further support the incorporation of proportional reasoning in the treatment group, since the text and online homework suite lacked this specific functionality. Eleven students attended these sessions; seven students were identified as using RAP and four students were identified as using DA on embedded exam questions. [The volunteer recitation sessions did not continue after Exam I.] Conversely, the control section (n=75) received traditional instruction during the lecture periods that emphasized solving problems using DA. The following examples illustrate how subjects were identified as using either RAP or DA in their submitted exam responses.

**Dimensional Analysis (DA)**

*How many grams of aluminum are required to completely react with 85.0 grams of iron (III) oxide, based on Equation 1?*

\[
\text{Fe}_2\text{O}_3 (s) + 2 \text{Al} (s) \rightarrow \text{Al}_2\text{O}_3 (s) + 2 \text{Fe} (s)
\]  

(1)

\[
\left(85.0 \text{ g Fe}_2\text{O}_3 \right) \left(\frac{1 \text{ mol Fe}_2\text{O}_3}{160 \text{ g Fe}_2\text{O}_3} \right) \left(\frac{2 \text{ mol Al}}{1 \text{ mol Fe}_2\text{O}_3} \right) \left(\frac{26.9 \text{ g Al}}{1 \text{ mol Al}} \right) = 28.6 \text{ g Al}
\]

**Figure 2. DA problem-solving that focuses on unit cancellations**

In a free response question that requires students to show their work, full credit is given if a student responds that 28.7g of Al required in this reaction and supplies their work as a version of the algorithm shown in Figure 2.
Ratio and Proportions (RAP)

\[
\text{1 mol } \text{Fe}_2\text{O}_3 : 2 \text{ mol of Al} \quad (2) \\
\text{1 mol } \left(160 \frac{\text{g } \text{Fe}_2\text{O}_3}{\text{mol}}\right) : 2 \text{ mol } \left(26.9 \frac{\text{g } \text{Al}}{\text{mol}}\right) \quad (3) \\
160 \text{ g } \text{Fe}_2\text{O}_3 : 53.8 \text{ g Al} \quad (4)
\]

A proportional relationship can be used to solve for the unknown variable.

\[
\frac{85.0 \text{ g } \text{Fe}_2\text{O}_3}{160 \text{ g } \text{Fe}_2\text{O}_3} = \frac{x \text{ g Al}}{53.8 \text{ g Al}} \quad x = 28.6 \text{ g Al}
\]

Figure 3. RAP problem-solving that focuses on proportional reasoning

The previous question detailed in Figure 2, regarding aluminum, can be also solved using RAP. Using the balanced equation (Eq. 1), a student can reason that 1 mole of Fe₂O₃ can completely react with 2 moles of Al. Then, using the molar masses of the starting materials [160 g/mol Fe₂O₃, and 27 g/mol Al], a student can reason that 160 g of Fe₂O₃ can completely react with 54 g of Al as shown in Figure 3 (equations 2 - 4).

How many atoms of Al must be added to a reaction to produce 4.25 x 10⁻³ moles of Al₂O₃, based on the following equation?

\[
\text{Fe}_2\text{O}_3 \text{(s)} + 2 \text{ Al (s)} \rightarrow \text{Al}_2\text{O}_3 \text{(s)} + 2 \text{ Fe (s)}
\]

\[
\begin{align*}
2 \text{ mol } \text{Al} & : 1 \text{ mol } \text{Al}_2\text{O}_3 \\
2 \text{ mol } \left(6.02 \times 10^{23} \frac{\text{atoms } \text{Al}}{\text{mol}}\right) & : 1 \text{ mol } \left(6.02 \times 10^{23} \frac{\text{particles } \text{Al}_2\text{O}_3}{\text{mol}}\right) \\
1.20 \times 10^{24} \text{ atoms Al} & : 6.02 \times 10^{23} \text{ particles } \text{Al}_2\text{O}_3
\end{align*}
\]

\[
\frac{x \text{ atoms } \text{Al}}{1.20 \times 10^{24} \text{ atoms } \text{Al}} = \frac{2.56 \times 10^{21} \text{ particles } \text{Al}_2\text{O}_3}{6.02 \times 10^{23} \text{ particles } \text{Al}_2\text{O}_3} \quad x = 5.10 \times 10^{21} \text{ atoms Al}
\]

Figure 4. An example of RAP problem-solving that includes a conversion

In the example detailed in Figure 4, a student will need to covert 4.25 x 10⁻³ moles of Al₂O₃ to the number of particles using Avogadro’s number (6.02 x 10²³), resulting in 2.56 x 10²¹ particles of Al₂O₃. Based on the balanced equation, a student can assume if 2 moles of Al yields 1 mole of Al₂O₃, then 1.20 x 10²⁴ atoms Al will yield 6.02 x 10²³ particles of Al₂O₃, as shown in equations 5 - 7. A student can produce a proportional
relationship and solve for the unknown number of Al atoms that must be supplied to facilitate this reaction as described in the balanced equation.

Results

Based on the experiment design, the average course grades and exam performances of the control and treatment students are equivalent (Table 2). An area in which the treatment group displayed a discernable difference of mathematical significance occurred on Exam II. The second exam focuses on gas laws (which have an inherent proportional relationship) and the application of stoichiometric relationship of dissolved gases and solutes in aqueous solutions. It is reasonable that the treatment group, which received instruction solving algebraic problems during the course with RAP, had a higher performance on the later exam due to their increasing familiarity with this algebraic process. Overall, the course grades and performance on the final exam were similar, as were the cumulative GPA’s of the two groups.

Table 2. Comparison of Average of Exam Scores and Total Course Percentage Points

<table>
<thead>
<tr>
<th></th>
<th>Exam I</th>
<th>Exam II</th>
<th>Final Exam</th>
<th>Total Course % Points</th>
<th>Cumulative GPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 75)</td>
<td>67.8</td>
<td>68.9</td>
<td>69.9</td>
<td>74.8</td>
<td>2.77</td>
</tr>
<tr>
<td>Treatment (n = 98)</td>
<td>69.2</td>
<td>75.6a</td>
<td>70.8</td>
<td>75.8</td>
<td>2.94</td>
</tr>
</tbody>
</table>

a $\rho = 0.0169$

Additional areas of significance are isolated when the treatment group is further separated based on the student’s use of RAP or DA on imbedded stoichiometric exam questions. The performance of students in the treatment population who solved problems using DA (n=68) was similar to that of the control group, as shown in Table 3. A majority the treatment DA students indicated a prior familiarity with DA stemming from their secondary education. Despite the fact that their college course instruction emphasized proportional reasoning, these students chose to retain their previously acquired problem-solving strategy. This could be a result of the use of a text and online homework system that reinforced the DA methodology. Students were repeatedly told that all problem-solving methods that could be justified would be awarded full credit to ensure students used the method with which they felt most comfortable.
Table 3. Comparison of Average Exam Scores and Total Course Percentage Points of Treatment DA Students

<table>
<thead>
<tr>
<th></th>
<th>Exam I</th>
<th>Exam II</th>
<th>Final Exam</th>
<th>Total Course % Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 75)</td>
<td>67.8</td>
<td>68.9</td>
<td>69.9</td>
<td>74.8</td>
</tr>
<tr>
<td>Treatment DA  (n = 68)</td>
<td>68.7</td>
<td>72.2</td>
<td>68.4</td>
<td>73.8</td>
</tr>
</tbody>
</table>

The performance of students in the treatment population who solved imbedded exam questions using RAP (n=30), demonstrated a mathematically significant improvement in each of the various categories, with the exception of Exam I, when compared with the control (Table 4). Solving chemistry problems using proportional reasoning is a deviation from traditional methods currently learned by many students. The period of adjustment could take sometime and may be the reason why the students’ performance on the first exam, which takes place in the fourth week of the course, is comparable to the performance of the control population. However, once the use of proportional reasoning has been studied for eight weeks, at the time of the second exam, the RAP students demonstrate a letter grade improvement on Exam II compared with the control. Even more impressively, these gains are maintained through the Final Exam and their course grade.

Table 4. Comparison of Average Exam Scores and Total Course Percentage Points of Treatment RAP Students

<table>
<thead>
<tr>
<th></th>
<th>Exam I</th>
<th>Exam II</th>
<th>Final Exam</th>
<th>Total Course % Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 75)</td>
<td>67.8</td>
<td>68.9</td>
<td>69.9</td>
<td>74.8</td>
</tr>
<tr>
<td>Treatment RAP (n = 30)</td>
<td>70.3</td>
<td>83.2b</td>
<td>76.4c</td>
<td>80.5d</td>
</tr>
</tbody>
</table>

b $\rho = 7.83 \times 10^{-6}$, c $\rho = 0.0237$, d $\rho = 0.0107$

The most intriguing findings surface as the performances of the RAP students within the treatment population is compared against their DA classmates. (Table 5) The use of RAP by students resulted in mathematically significant higher performances on Exam II, the Final Exam, and in their course grade. The only difference between these set of students is their choice of problem solving strategies. Although the cumulative GPA of the treatment RAP students is slightly higher, the two groups are analogous and their GPAs and did not reflect a mathematically significant difference; therefore the academic aptitude of the two groups is comparable.
Table 5. Comparison of Average Exam Scores and Total Course Percentage Points of Treatment DA with RAP Students

<table>
<thead>
<tr>
<th></th>
<th>Exam I</th>
<th>Exam II</th>
<th>Final Exam</th>
<th>Total Course % Points</th>
<th>Cumulative GPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment DA (n = 68)</td>
<td>68.7</td>
<td>72.2</td>
<td>68.4</td>
<td>73.8</td>
<td>2.90</td>
</tr>
<tr>
<td>Treatment RAP (n = 30)</td>
<td>70.3</td>
<td>83.2(^{g})</td>
<td>76.4(^{f})</td>
<td>80.4(^{g})</td>
<td>3.17</td>
</tr>
</tbody>
</table>

\(e \rho = 5.28 \times 10^{-4}, f \rho = 0.00801, g \rho = 0.00460\)

Since the use of RAP in this study was neither supported in the textbook nor in the online homework suite, the treatment group population was offered the opportunity to attend a 60-minute volunteer recitation session (during weeks 2 - 4 of the course) that focused on solving stoichiometric problems using proportional reasoning. Eleven students from the treatment population attended these sessions. Seven were identified as using RAP and four were identified as using DA to solve stoichiometric problems on embedded exam questions. It should be noted that these sessions did not continue after the first exam. The comparison of these students who spent additional time-on-task using RAP was compared to the control group in Table 6. Two areas of mathematical significance emerged when these groups were compared. In the control group their scores on the Exams I and II and the Final remained flat. Conversely, the performance of the recitation students rose by a letter grade (compared to their Exam I performance) and can be equated with the additional time-on-task in employing the proportional reasoning methods presented during instruction.

Table 6. Comparison of Average Exam Scores and Course Grades of Recitation Treatment students

<table>
<thead>
<tr>
<th></th>
<th>Exam I</th>
<th>Exam II</th>
<th>Final Exam</th>
<th>Total Course % Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n = 75)</td>
<td>67.8</td>
<td>68.9</td>
<td>69.9</td>
<td>74.8</td>
</tr>
<tr>
<td>Recitation Treatment</td>
<td>68.4</td>
<td>82.1(^{i})</td>
<td>76.0</td>
<td>80.4(^{i})</td>
</tr>
<tr>
<td>(n = 11)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(h \rho = 0.00759, i \rho = 0.0497\).

The recitation students also provided additional qualitative data of note. Three RAP students from the recitation population scored below the class averages on Exam I, but demonstrated double-digit performance gains on Exam II and the Final Exam in comparison with their Exam I performance. Their averaged performances were as follows: Exam I [57 (6.9 sd)], Exam II [87 (9.2 sd)], Final Exam [75 (3.5 sd)], and Total Course Percent Points [78.3 (1.76 sd)]. Based on their initial performance on Exam I.
these students were in jeopardy of failing the course, yet their persistence with proportional reasoning led to a large elevation in their Exam II and Final Exam scores. Further investigation could lead to a correlation in these student’s increased reasoning skills and their ability critically analyze through the use of RAP.

On the final exam, the treatment population was given an optional problem-solving page in which the class was instructed to solve two stoichiometric problems using an assigned method by the instructor. Fifty percent of the students were assigned to solve the first problem with RAP, and the other students were assigned to solve the first problem using DA. The assigned method then alternated for each student in regards to the second problem. Additionally, students were required to provide a written response that explained how they approached solving the various problems. All three of the identified RAP recitation students (described above) completed both problems using RAP and DA and earned at least 85% of the possible credit. On the question in which these students were assigned to use RAP, their exam question was as follows:

_A common laboratory preparation of oxygen gas is achieved through the decomposition of potassium chlorate in the presence of a catalyst. At standard temperature and pressure, calculate the mass (in grams) of oxygen gas that is generated from 46.0 grams of potassium chlorate using the following equation._

\[
2 \text{KClO}_3 (s) \rightarrow 2 \text{KCl} (s) + 3 \text{O}_2 (g)
\]

Each student set up a valid proportion. However, one student incorrectly used the molar mass of KClO_4 instead of KClO_3. The second student miscalculated the molar mass of oxygen gas (O_2) as 16 g/mol instead of 32 g/mol. This error neglected the presence of two atoms of oxygen in the elemental form of the diatomic gas. The third student received full credit. One student chose to write a proportion that was mole-based and included the stoichiometric coefficients from the balanced equation. The other two students chose to write a gram-based proportion that included the stoichiometric coefficients and corresponding molar masses. In the written explanation section of the question, each of the students mentioned the balanced equation, the mole concept, and identified that the mole ratio of the balanced equation were key in their algebraic solving technique.

Qualitative Analysis

The use of RAP in this study provides chemistry students the ability to reflect on the importance of the balanced equation and how it governs quantitative relationships on multifaceted levels. The performance of students using the various methods shows the various problem-solving methods are algebraically equivalent. Similar to DA, RAP can be extended to stoichiometric calculations in which the measured value is given in to the student in moles, mass, molecules, or volume and the problem requires them to solve for a related unknown variable using the balanced equation and inherent stoichiometric mole ratios. Instruction that supports the incorporation of proportional reasoning within
problem-solving techniques results in the elevation of student performance on exams and courses grades compared to students who used DA. Ultimately, the determining factor is the student’s individual choice to use RAP as opposed to DA.

A student from this study, who was taught DA in high school and chose to utilize RAP during this college course, submitted the following reflection.

“[In previous classes] I was very confused about DA. I understood how to solve the problems but did not grasp the reasons behind why the units cancel. I was solving problems with no knowledge of how stoichiometry really works. After learning RAP, I understood how the equations react. Using RAP I see how important the balanced equation is in respect to all the compounds. In the DA method I did not really learn how the chemical reaction occurs, I only answer if the units properly cancel.”

Others have agreed that students who use DA are relying on the cancelation of units to guide their worked solution. (Tykodi, 1987) As shown in Figure 2, DA encourages students to express their work as an extended algorithm of unit cancelation. (Frank et al., 1987) Moreover, DA does not promote student understanding of chemical reactions. (Cameron, 1985; Karp, 1988) In fact, an instructor’s over-emphasis of this approach may limit student learning to the problem-solving method itself. (Cardulla, 1987) Some have found that students, who earn high marks for correctly implementing DA, lack the ability to verbally explain the mole and the proportionality of a balanced equation without prompts. (Gabel et al., 1984) Others have offered that even when students correctly use coefficients from the balanced equation in stoichiometric algorithms, they still do not understand the concepts (on the particulate level) that a balanced chemical equation is trying to convey. (Nurrenbern & Pickering, 1987; Sanger, 2005) A student from this study submitted the following written response as an explanation to describe their problem-solving strategy using DA on the optional problem-solving page of the final. “Dimensional Analysis is effective, I lined everything up correctly as far as units and begin to cancel and solve.”

Instructors must equip students with tools that will benefit them in introductory and advanced courses that may not always support the notion of quick clean transformations. Students must be given opportunities to develop as critical thinkers. This growth should include comprehension of the proportional relationship of laboratory mass values and how they are governed by the balance molecular equation.

Discussion

Based on our findings, a student’s ability to proportionally reason is an accurate indicator of a student’s success in STEM-based disciplines. A student’s choice to incorporate RAP on embedded exam questions resulted in mathematically significant improvements over a ten-week period that could be identified in the second exam, the final and in the course grade of the treatment population. The authors will continue to investigate if the
incorporation of proportional reasoning in lecture instruction, chemistry textbooks, and online homework suites lead to similar findings. Additional tools will be implemented to identify which aspects of RAP are influencing these positive results in future studies. Additionally, pedagogical techniques of supporting proportional reasoning in student work should have similar effects in secondary-level science courses and result in the matriculation of students who have additional fortitude in the use of RAP. Chemistry faculty must be careful to use DA instruction in moderation. The incorporation of proportional reasoning with an emphasis on the balanced equation provides opportunities for students to continually develop as critical thinkers while solving stoichiometric exercises.

**Authors’ Biographies**

**Dr. Michael F. Z. Page** is an alumnus of Xavier University (BS), UCLA (PhD), and performed his postdoctoral studies at California Institute of Technology. As a tenure track faculty at California State Polytechnic University, Pomona, Page has focused on science education, the professional development of secondary educators, and the development of green polymeric materials. Since 2007, Michael has hosted several teacher workshops at Cal Poly Pomona. He has received several teaching awards including the College of Science Distinguished Faculty Award. His Chemical Education research has focused on the use of Proportional Reasoning in the General Chemistry classroom instruction of stoichiometry.

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**Cynthia Guevara** is a senior at California State Polytechnic University, Pomona. Guevara has been involved in STEM education workshops from 2009-11. In 2009, she began her Senior Research Project involving college student enrolled in General Chemistry. This research analyzes the impact of an alternative problem-solving method in teaching of stoichiometry utilizing Ratio and Proportions. We believe this problem-solving method allows students gain a deeper understanding of how chemical reaction masses are proportionally related to the balanced equation and the mole concept. By expanding this research she is continuing her senior research project by incorporating ratio and proportions in high school classroom instruction.

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**Dr. Edward Walton** is Professor of Chemistry at “Cal Poly Pomona”. He has taught at the US Naval Academy, and worked at the Lawrence Hall of Science, Berkeley, as statewide pre-college program coordinator for the Math Engineering, Science Achievement Program. He has taught general chemistry, advanced inorganic chemistry, consumer chemistry, and the “Methods for Teaching Science”. He has worked with the National Assessment for Educational Progress in Science, the Educational Testing Service, and the National Academy of Sciences’ group that developed the National Science Education Standards. He conducts summer science teaching institutes for elementary, middle, and high school chemistry teachers.
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