

# A Rubric for Assessing Students' Experimental Problem-Solving Ability

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## S Supporting Information

**ABSTRACT:** The ability to couple problem solving both to the understanding of chemical concepts and to laboratory practices is an essential skill for undergraduate chemistry programs to foster in our students. Therefore, chemistry programs must offer opportunities to answer real problems that require use of problem-solving processes used by practicing chemists, including those of experimental design. Additionally, programs should assess the extent to which these skills are mastered by students and use the results to inform curricular development. This manuscript describes a rubric for experimental problem solving in chemistry that seeks to assess the extent to which students can both understand a chemical problem and design an instrument-based strategy to address it. The rubric effectively differentiates responses to practicum questions answered by students at different stages of the undergraduate chemistry curriculum. The data show that students improve in their ability to problem solve as they progress through the program. On average, students are able to provide a "correct" answer before they are able to articulate a complete understanding of the problem or to justify their choices. The rubric will be useful to others seeking to study or assess student problem-solving skills at both the course and curricular levels.

**KEYWORDS:** *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Chemical Education Research, Testing/Assessment*

**FEATURE:** Chemical Education Research

The 2008 American Chemical Society Guidelines for undergraduate chemistry programs enumerate a variety of skills that undergraduate students should develop in the course of earning a baccalaureate degree.<sup>1</sup> Among these is problem solving, which is described as the ability to "define a problem clearly, develop testable hypotheses, design and execute experiments, analyze data, and draw appropriate conclusions".<sup>1</sup>

Because of the central role of problem solving in the education of undergraduate chemistry students, it is essential that programs identify ways to assess it. Assessment done well allows programs to determine the extent to which a course or program successfully supports student learning of problem-solving skills, to identify gaps in the curriculum, or to determine the extent to which a course or curricular change is effective at supporting student learning. To this end, instructors and departments must have strategies in place to collect and analyze relevant student learning data. In many cases, it is appropriate for course-specific assignments to provide information about student learning. However, tools that can be used for assessment of individual student work both within a course as well as student learning across the curriculum are also valuable.

This manuscript describes the development and application of an assessment strategy aimed at understanding the extent to which students were able to think critically about or solve laboratory-based problems across the curriculum, with particular attention to the application of chemical instrumentation. We were interested in the extent to which students can understand a

chemical problem and design an instrument-based strategy to address it, both of which are specific components of the larger set of problem-solving skills. We wanted to characterize these skills at different stages of students' undergraduate academic development so that we could better scaffold their learning these skills throughout the curriculum.

Cognitive skills, such as critical thinking or problem solving, are difficult to measure with a conventional "test", graded for correct versus incorrect answers. However, a rubric can allow characterizations of student thinking or understanding. A rubric is an assessment tool that identifies features that student work should have, along with several levels of quality of student work that might be associated with each feature. Rubrics used for assessment in chemistry have been designed to assess students' understanding and scientific thinking by evaluating their written or oral communication,<sup>2,3</sup> the quality of their arguments, or explanations or use of domain knowledge in chemistry.<sup>4-6</sup> To assess students' ability to use their knowledge of standard chemical instrumentation to address experimental chemical problems, we developed a set of open-ended questions (referred to as practicum questions) and a rubric to evaluate students' responses to these questions. Because the reliability of a rubric is improved in part by being topic-specific,<sup>7</sup> we chose to develop a rubric for experimental problem solving in chemistry. The rubric is designed to probe the accuracy of

Published: January 24, 2012

student thinking, the quality of students' explanations, and the extent to which students understood an experimental problem connected to laboratory instrumentation.

This assessment strategy has been used to assess student learning at different stages in the undergraduate chemistry curriculum. We expected that student progression from lower-division to upper-division courses would result in improvement in the quality of their responses to challenging questions because their understanding of both chemical content and the process of problem solving should improve as they constructed a richer understanding of chemical concepts and experimental design.

## METHODS

### Rubric Development

Because we began with an interest in our students' problem solving and critical thinking skills, we consulted an existing critical thinking rubric,<sup>8,9</sup> as we designed a new rubric that could be used to score student responses to practicum questions. We selected the following critical-thinking

features that applied to the type of questions we were asking of students:<sup>8,9</sup>

- The student identifies the problem and the underlying issues.
- In formulating a hypothesis or position, the student presents, assesses, and analyzes appropriate supporting data and evidence.
- The student addresses multiple perspectives and positions that should be considered for solution of the problem.

As we used the rubric to score a limited number of student responses to an initial set of questions (used in Spring and Fall 2008), we refined the rubric traits to reflect what we valued in student work and to capture the variation we observed in student responses. After a number of iterations with this initial set of questions and student work from several different courses in the curriculum, we arrived at the final rubric (see Figure 1), which focused on the extent to which a student response:

- Identifies the important or relevant features of the problem.

<b>Criterion 1. Identifies the important or relevant features of the problem.</b> For each practicum question, students will be provided a problem. This dimension is related to student identification of the important issues that must be considered in order to solve the presented problem.			
<i>Emerging</i>	<i>Developing</i>		<i>Mastering</i>
1	2	3	4
Does not attempt to or fails to identify the important aspects of the problem... clueless.	Identifies a small percentage of the important features of the problem to be solved.	Identifies some of the important features of the problem.	Clearly demonstrates an understanding of the problem, addressing important aspects of the problem that must be considered.
<b>Criterion 2. In formulating a strategy for the solution of the problem, student presents a complete justification or explanation for the strategy.</b> This dimension focuses on the ability of the student to back up the choice of strategies with appropriate reasoning and factual, procedural, or conceptual knowledge. This dimension also deals with the completeness of one's strategy.			
<i>Emerging</i>	<i>Developing</i>		<i>Mastering</i>
1	2	3	4
Strategy is incomplete and/or lacks justification.	Justification is provided for most or all components of the strategy, but the reasoning is limited to the most basic information.	Provides a complete explanation with reasons for choosing the components of the strategy.	Includes all reasons for choosing the components of the strategy, and also includes caveats and reasons not to choose alternative strategies.
<b>Criterion 3. Provides an effective strategy that is likely to work to solve the chemical problem.</b> This dimension focuses on the correctness of the strategy a student chooses to address the problem: would it work? This strategy also deals with student identification of reasons it may not work.			
<i>Emerging</i>	<i>Developing</i>		<i>Mastering</i>
1	2	3	4
The data to be collected will provide limited information for solving the stated problem.	The data to be collected are likely to provide insight into the stated problem, but the results will be less than definitive. Student appears to have made some unstated assumptions.	Data to be collected are likely to yield definitive results, leading to an unambiguous answer to the stated question.	Data to be collected are likely to yield definitive results, leading to an unambiguous answer to the stated question. In addition, answer includes information about why the strategy may not work. Answer may also indicate back-up strategies that could be employed.

**Figure 1.** Rubric for experimental problem solving in chemistry. The rubric is designed to measure the extent to which a student response to a given problem identifies the important or relevant features of the problem, presents a complete justification or explanation for the strategy, and provides an effective strategy that is likely to work to solve the chemical problem.

- While formulating a strategy for the solution of the problem, presents a complete justification or explanation for the strategy.
- Provides an effective strategy that is likely to work to solve the chemical problem.

The rubric was then applied to a new set of questions that were given to students in Spring and Fall 2009. Before using the rubric to score the student responses, at least two content experts created exemplar answers to the questions because the use of exemplars increases the reliability of the rubric scoring.<sup>7</sup> (See the online Supporting Information for practicum questions and exemplar answers.)

## ■ PRACTICUM QUESTION DEVELOPMENT

The rubric was developed to examine students' ability to draw on their knowledge of chemical instrumentation, experimental design, and chemical concepts to solve problems in chemistry as they progressed through our program. To accomplish this, we developed a different set of "practicum questions" that were administered to students during each academic year cycle and the student responses to these practicum questions were evaluated using the rubric. To solicit answers that included the elements we deemed important (as determined while the rubric was being developed), the questions were designed to adhere to specific criteria. First, in order to differentiate answers provided by anyone enrolled in the program, we determined that the questions should have elements that are answerable by students at all levels, irrespective of whether they are just beginning or about to graduate from the program. Next, the questions should be probing and open-ended in order to compel students to provide complete answers that can easily be differentiated upon evaluation. Related to this, it was our experience that students would provide more elaborate answers if they were asked multipart questions that were structured to solicit a single coherent paragraph rather than individual answers to each subquestion. This was especially true of the beginning students. Fourth, while the questions should have familiar elements or concepts, they should also challenge students to apply the concepts to unfamiliar topics in order to prevent simple regurgitation of memorized facts or theories. Finally, we decided that the questions should be based on real problems with a best answer (or several best answers). This way, one or more "expert" answers can be used as exemplars when evaluating student responses. A description of our practicum questions that aim to meet our stated criteria follows, and a complete set of questions and exemplar answers are included in the online Supporting Information.

Each year when we administered our practicum questions, we included three subquestions that required students to provide answers to chemical problems that had been previously reported on in the chemical literature. The set of three questions involved characterizing products (typically present in a mixture), measuring reaction rates, and deconvoluting complex mechanisms. To help students reduce the amount of completely new material they would have to work to understand, we chose to connect the set of questions around a theme. For our purposes, it was convenient to use transition metal-catalyzed reactions as our foci for two reasons. Namely, the reactions have been quite well studied and offer rich mechanistic detail. We also have chemical expertise with these types of systems, which allows us to develop meaningful problems for students to answer. Themes we have used include reactions and mechanisms of the Stille

reaction,<sup>10,11</sup> ring closing metathesis,<sup>12–14</sup> and the ring-opening of meso epoxides with the Jacobsen catalyst.<sup>15,16</sup>

While the questions were written to be challenging to all students, we also intentionally created questions with parts that would be answerable regardless of the point the student is at in the undergraduate curriculum. For the first of the three questions, for example, students are presented with the problem of characterizing the products of an organic reaction that is facilitated by a transition metal catalyst and typically produces a mixture of two or three main products. Students are asked to identify three instruments that they would use to: (i) verify the identity of the organic products; (ii) determine that no starting material remained; and (iii) determine that the products were formed in the ratio that is stated. To provide a complete answer, students were also asked to specifically identify the information each instrument would provide, as well as which instrument is the most important and why. These types of questions allowed the beginning student to focus on methods for determining the structural differences between the products and reactants, whereas the advanced students were able to attend to the more subtle issues that were present.

The remaining two questions within each set were somewhat similar to the first in that there were some components that can be addressed by students at all levels, although with expanded scope and complexity. The second question typically provided information concerning the kinetics and reaction order of a chemical transformation. Students were asked how they would verify this information, specifically identifying what instrument(s) they would use, what the observable(s) would be, and what would they expect to see. The third question was analogous, except that there were multiple components to the mixture, and students were asked to describe the experiment from start to finish. In both cases, questions ask students to state any assumptions and any potential drawbacks to their approach. See Figure 2 for an example of the third type of question (and the online Supporting Information for a complete set of practicum questions and exemplar answers).

## Administration of Practicum Assessments

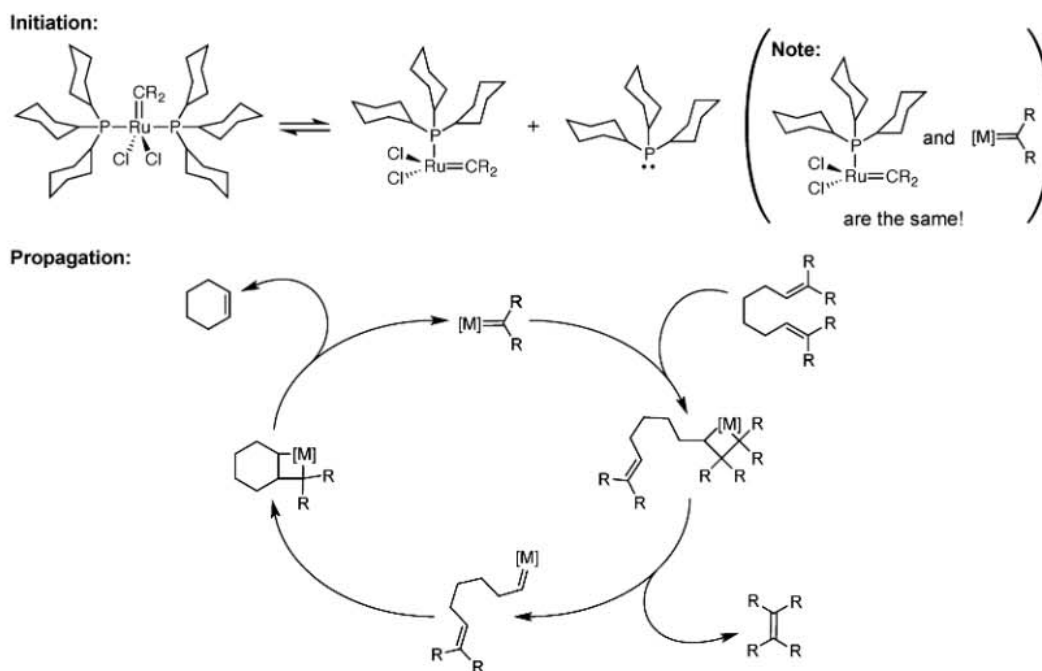
Our goal was to capture student knowledge and problem-solving skill level at different stages in our chemistry curriculum. Thus, each set of practicum questions was administered to students at different stages. Table 1 describes the cohorts of students who completed the practicum tests.

The Soph 1 and Soph 2 cohorts are made up of students from many majors. The Junior and Senior cohorts are chemistry majors. Each practicum test was administered as part of a laboratory or seminar course. It was treated as a "take home" assignment and students were instructed to independently answer the questions to the best of their ability without any outside resources (i.e., Internet, textbooks, friends, etc.). Students in the Soph 1, Soph 2, and Junior cohorts received a small amount of points (<2% of their final laboratory grade) for completing the questions. Seniors were not given any credit, but told that they would not receive a course grade until the questions were turned in. With all of the cohorts, students received credit if they put forth a good effort while attempting to answer the questions.

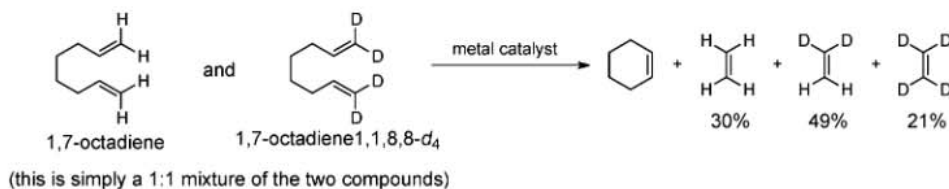
## Practicum Assessment Scoring

The first set of practicum questions was administered in 2008 (spring and fall) and was used to refine the rubric. A second set of practicum questions was administered in 2009 (spring and fall) to four cohorts: Soph 1,  $N = 110$ ; Soph 2,  $N = 76$ ; Junior,

The proposed mechanism for RCM involves a chain reaction. The initiation and propagation steps are shown below.



While attempting to provide support for this mechanism, researchers conducted a reaction with a 1:1 mixture of 1,7-octadiene ( $R = \text{hydrogen}$ ) and 1,7-octadiene-1,1,8,8-d<sub>4</sub> ( $R = \text{deuterium}$ ). After 5% of the starting diene had been consumed, the reaction was stopped. It was found that the products of the reaction were cyclohexene, ethylene, ethylene-1,1-d<sub>2</sub>, and ethylene-1,1,2,2-d<sub>4</sub>. The ethylene isotopes were isolated in the ratios shown.



If you were assigned to verify these results, what one instrument would you use? Why would you use this instrument? How will this instrument allow you to differentiate the products from the starting materials? How will you measure the product ratios? How would you determine when the reaction is 5% complete? Be specific in all of your answers. Describe, for example, the experiment from start to finish. What would you expect to see? What assumptions would you make? What are some drawbacks/challenges to your approach?

**Figure 2.** Question 3 from a set of practicum questions that focused on ring-closing metathesis. The question was intended to involve components of structural identification, reaction monitoring, and relatively complicated mechanisms. This question was based upon published experimental work.<sup>12</sup>

**Table 1. Schedule for Students Completing the Practicum Assessment**

Cohort	Description	Semesters of Chemistry Coursework Typically Completed at Time of Assessment
Soph 1	Test administered at beginning of organic chemistry, as part of first-semester organic laboratory	2 semesters (general chemistry)
Soph 2	Test administered at end of organic chemistry, as part of second-semester organic laboratory	4 semesters (those above, plus organic chemistry and analytical chemistry/quantitative analysis)
Junior	Test administered at end of students' first semester of junior-level laboratory work	5 semesters (those above plus one semester of physical chemistry and a junior-level laboratory course)
Senior	Test administered at end of students' final semester in the program, as part of senior seminar capstone course	8 semesters (those above, plus second-semester physical chemistry, second-semester junior-level laboratory, and senior-level coursework: for example, biochemistry/lab, advanced inorganic, spec ID, senior research)

$N = 17$ ; Senior,  $N = 6$ . The smaller cohorts at the Junior and Senior levels represent 100% of the students enrolled in courses that year. The Soph 1 and 2 cohorts represent 91% and 93%, respectively, of the students enrolled in the organic courses when the questions were administered. All students whose data

are included in the study consented to have their responses included. The methodology for this study was approved by our Human Subjects Institutional Review Board. Each set of student responses was scored by three researchers. For each set of practicum questions, the exemplar answers were used to

identify the components of an answer that would be awarded the highest rubric score in each category. (See the online Supporting Information for a set of exemplar answers.) Before scoring began, the three scorers discussed what one should expect to find for each of the rubric scoring categories at each level. Scoring one question at a time, researchers scored that question on all three characteristics of the rubric. Initially, this involved discussing each student answer and how to apply the rubric consistently. Once established, the researchers scored 5–10 student responses and then stopped to compare scoring results. Scores that spanned more than two adjacent scale values between the three scorers (e.g., 1, 2, and 3; or 2, 3, and 4), were automatically discussed until one or more scorers were convinced to modify his or her score to achieve the “within a one adjacent value” criterion. Occasionally, discussion also caused a researcher to change a score to be consistent with others. This “forced adjacent agreement” process was then repeated for all of the responses to the second and then to the third question on the practicum. As facility with the rubric as a scoring tool grew, the discussions were less necessary to maintain consistency. For the 2009 practicum results, final scoring reflected an inter-rater reliability of 80%, meaning that on 80% of the rubric criteria for all three questions, all three scorers had exactly the same score. On the basis of our procedure, all of the scores were no more than one scale value different from the others. Scores are reported as averages from the three researchers. The process of scoring the 209 student papers used in this study required approximately 20 h.

Because each question was scored on three rubric criteria and each criterion was awarded a minimum score of 1 and a maximum score of 4, the maximum score a student could receive on the practicum question set is 36 (a 12-point sum for the three criteria on each of three questions) and the minimum score a student could receive is 9 (a 3-point sum for the three criteria on each of three questions).

## RESULTS AND DISCUSSION

A set of three practicum questions, including the one in Figure 2, was administered to a total of 209 students during the Spring and Fall 2009 semesters. Evaluation and scoring of each student's answers was undertaken using the rubric presented in Figure 1. To demonstrate the application of the rubric, the analysis of representative answers provided by two students, one in the Soph 1 cohort and the second in the Senior cohort, is presented in Boxes 1 and 2. The question score for the Soph 1 student answer was a 3 out of 12, based on a score for each criterion of 1. Thus, this student received the lowest possible score for this question. In comparison, the Senior student received a question score of 11, with scores of 3, 4, and 4 for criteria 1, 2, and 3, respectively. The rationale for assigning the scores is as follows.

In the rubric, criterion 1 evaluates the student's ability to identify the important or relevant features of a problem that must be considered in order to solve the problem. Students at the “mastering” level clearly demonstrate an understanding of the problem, addressing all of the important aspects of the problem, as determined by comparison to an exemplar. For this particular problem, students needed to acknowledge the importance of the phase of the products for purposes of separation, identify the time-dependent element of the problem, include a reference to a strategy to differentiate the various products (e.g., by mass), and identify the need for the use of an internal standard or some other calibration strategy. The student in the Soph 1 cohort provided an answer that received a score

“I would use a balance because it allows me to measure the mass of the products if I am able to separate them. The weight of the compounds will allow me to differentiate the products from the starting materials. I will measure product ratios by comparing the mass. I would determine the reaction is 5% complete by the weight of the products. I would expect to see the weight of the reactants shift to the weight of the products. I assume that the products are solid and crystallized so they can easily be separated from the rest of the solution. The drawback to my approach is the products may be nearly impossible to remove from the reaction.”

Box 1. Representative answer from a student in the Soph 1 cohort to the example ring-closing metathesis question 3 from Figure 2.

“I would use GC/MS because it would separate reactants and products and allow the analysis of each one individually. The methods could be setup to separate all 5 compounds, which may take some time. The product ratios could be compared by peak intensities, relative to an internal standard. Aliquots could be taken throughout the course of the run and analyzed. Once the products reach 5% of the reactant stop the reaction. The aliquots would be prepared for analysis by diluting if needed, adding an internal standard then injecting the sample. Analysis of the peak intensities and retention times to get product ratios. I am assuming that the compounds can be separated by GC in this description. I am also assuming that the reaction is very slow as it would not work in fast reactions. The largest challenge to this approach would be developing the instrument methods.”

Box 2. Representative answer from a student in the Senior cohort to the example ring-closing metathesis question 3 from Figure 2.

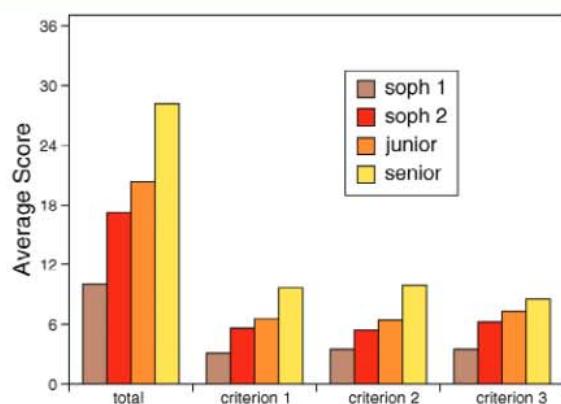
of 1 for this criterion, the metric of which states “Does not attempt to or fails to identify the important aspects of the problem... clueless”. This student, who is at the very beginning of organic chemistry, relies solely on the use of macroscopic mass measurements for all aspects of the question. Although the student is unable to provide a correct answer to the question, the answer makes sense given that students in general chemistry have had significant experience with balances, but little else beyond this. In contrast, the student in the senior cohort provides a much more complete answer. On the basis of comparison to the exemplar, the student fails only to consider how to sample a gaseous product and consequently receives a score of 3 out of 4 for this criterion.

Criterion 2 is used to evaluate a student's articulated strategy for solving the problem and the extent to which a student presents a complete justification or explanation for the strategy, with attention to appropriate reasoning and factual, procedural, or conceptual knowledge. This criterion also evaluates the completeness of a strategy. Students at the mastering level fully justify their strategy, and also include caveats and reasons not to choose alternative strategies. This criterion is such that even if a student completely misses the point with respect to identifying the important aspects of a problem, they can obtain a reasonable score in this category as long as they fully justify their strategy. In the case of the Soph 1 student, there is no detail about how mass measurements will be used to solve the problem. For example, it is stated that he or she “would determine the reaction is 5% complete by the weight of the products”. This

answer would have been given a higher score if the student articulated the need to monitor the disappearance of starting material or appearance of products over time, using the mass and balance (although this would clearly not work). The Senior cohort student includes a quite well developed strategy that includes assumptions and caveats, even to the point of commenting on GC–MS method development and co-injecting an internal standard for measuring product ratios as part of the strategy.

Criterion 3 is used to evaluate whether or not the student has provided an effective strategy that is likely to work to solve the chemical problem, leading to definitive results and an unambiguous answer to the stated question. Answers at the mastering level will also include reasons why the strategy may not work and will indicate back-up strategies. When evaluating student answers with respect to this criterion, a student can obtain a 3 out of 4 by simply listing an instrument (or instruments) that will provide definitive results in the hand of an expert, even if the student receives low scores on the previous two criteria. To receive a score of 4, a student needs to also include back-up strategies and drawbacks to the proposed plan. The balance-based strategy provided by the Soph 1 student received a score of 1 because it will clearly not solve the stated problem, even though it includes one drawback. The Senior student received a 4 because the original literature account of this problem suggests that GC–MS should work.<sup>12</sup> Additionally, this student provides several potential pitfalls that must be overcome in order for the experiment to go smoothly.

On the basis of the above discussion, it is apparent that the rubric can differentiate between answers provided by students at the extremes of their undergraduate chemical education. When used to evaluate student answers from all four cohorts, summed over all three questions in the practicum, as shown in Figure 3,



**Figure 3.** Average student practicum scores, evaluated using the rubric in Figure 1, and averaged across all three questions on the practicum. The results demonstrate an improvement exists in student responses as students advance through the chemistry curriculum. The lowest possible score for each individual criterion is 3 points, while the maximum is 12 points; the maximum total score is 36. Soph 1,  $N = 110$ ; Soph 2,  $N = 76$ ; Junior,  $N = 17$ ; Senior,  $N = 6$ .

it is clear that the tool is effective at measuring more subtle differences in students' problem-solving and critical thinking competency as they move through the curriculum. With respect to total scores, one can see that there is a significant increase between Soph 1 and Soph 2 cohort scores and then again between Junior and Senior scores. The trend makes sense within the context of the current chemistry laboratory curriculum in which general chemistry students gain minimal exposure to

chemical instrumentation, whereas students rely on a variety of instrumentation for almost every experiment during organic chemistry. Additionally, between the middle of the Junior year (which is when the assessment is administered) and the end of the Senior year, students will have completed at least two additional upper-division lab courses and at least two semesters of undergraduate research. In contrast, only one junior-level laboratory class separates students in the Soph 2 and Junior cohorts. The scores on the individual criteria generally follow those of the total scores, with a significant increase between Soph 1 and Soph 2 and then again between Junior and Senior. The one criterion that does not follow this trend as clearly is that of criterion 3. While a student's ability to articulate an effective strategy for solving the problem trends upward through the curriculum (with a large increase after Soph 1), this criterion is not characterized by a large increase between Junior and Senior cohorts. This suggests that students are able to recognize potential applications and uses for instrumentation after only a few semesters of undergraduate study in chemistry, which are measured by criterion 3. However, it is not until they have had significant upper-division course experience that they are able to identify and understand the intricacies of a chemical problem and articulate more complete solutions, as measured by criteria 1 and 2. Students in the Senior cohort are most able to satisfactorily identify, describe, and justify a solution to a problem.

## CONCLUSIONS AND IMPLICATIONS

It is important that undergraduate chemistry programs prepare students for the kinds of problem solving they are likely to do (or need to understand) as practicing chemists or as professionals in other science-related careers. This practice is heavily dependent on the understanding of both experimental design and the use of instrumentation. Thus, it is essential that chemistry programs offer opportunities for students to develop these skills, assess the extent to which these skills have been mastered by students, and use the assessment results to improve the support for student learning outcomes related to problem solving. This project has focused on the development of a strategy to accomplish such assessment. The rubric for experimental problem solving in chemistry and practicum structure described herein is important because it complements other strategies currently available for assessment.<sup>17</sup> The rubric effectively differentiates answers to practicum questions provided by students at different stages of the undergraduate chemistry curriculum.

While a more thorough analysis and multiyear assessment will be reported subsequently, the results from this application of the rubric demonstrate students' improvement at this kind of problem solving as they move through our undergraduate curriculum. Importantly, the results also provide some interesting questions to consider. For example, students (on average) appear to be able to provide a "correct" answer (criterion 3) before they are able to articulate a complete understanding of the problem or to justify their choices (criteria 1 and 2). This pattern may reflect normal patterns of student development, which show that students early in their college career tend to view knowledge as a set of knowable answers to be repeated back on assignments or tests.<sup>18</sup> However, it may be that in the early courses we are not doing as much as we could to support student development of these kinds of problem-solving skills. These results allow us to look carefully at the curriculum and consider changes.

It is also interesting to consider what component of our curriculum supports student growth. Is this problem solving primarily supported by laboratory courses, a combination of the

lecture and laboratory formats, or primarily by involvement in lecture-based courses? Our results do not allow us to answer this question in any definitive way. However, the data show that the biggest gains in the problem-solving skills associated with criteria 1 and 2 come in the later semesters of our program, which are characterized by a heavy emphasis on laboratory work and undergraduate research, suggesting that these components of the curriculum are likely to play an important role in student growth and development. Future assessment is planned to look more carefully at the role of exposure to and use of particular instrumentation in the laboratory over multiple semesters and its relationship to the development of these important problem-solving skills.

Although our data collection and analysis are still under way, we have used the results from this application to implement some initial changes to the curriculum. Upon examination of student responses from the Soph 1 cohort, it was obvious that students in our general chemistry courses were not being adequately exposed to scientific instrumentation. Students in this cohort most frequently relied upon balances and graduated cylinders as their tools of choice. To attempt to partially remedy this deficiency, we have developed and implemented two new general chemistry experiments that use common instrumentation, namely, a gas chromatograph<sup>19</sup> and an infrared spectrometer.<sup>20</sup> The impact of the new experiments will be ascertained during the next phase of data collection.

While the application of the rubric in this study provides information about development of problem-solving skills at the program level, the strategy is flexible, as the rubric could also be used at the course level to provide individual instructors with information about student learning. For example, the rubric might be used to score exam questions similar to the practicum questions used in this study, or to assess a student research proposal or design assignment. Additional criteria could be added to the rubric to extend its utility in probing additional features of student learning.

For departments or instructors considering the use of such a strategy for assessment across the curriculum, we offer the following suggestions. First, question structure requires careful consideration in order to avoid terse, one-sentence answers. Second, administration of the practicum questions must be accomplished in such a way to compel students to take the time to provide thoughtful, complete answers. In most instances, awarding points or the threat of an incomplete provided sufficient motivation. For the Soph 1 cohort we also had to provide reassurance that there was no one right answer, as students had the immediate tendency to want to perform an Internet search, given the unfamiliarity of the questions. Finally, while the scoring of 209 student papers took considerable time (~20 h), we suggest that the time could be reduced by sampling student work or by looking only at the work of majors.

## ■ ASSOCIATED CONTENT

### 📄 Supporting Information

A complete set of practicum questions, exemplar answers, and average student scores for all three questions. This material is available via the Internet at <http://pubs.acs.org>.

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## ■ ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the NSF (DUE #0737128) for support of this project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Additionally, we would like to acknowledge Aaron Bruck, Department of Chemistry, Purdue University, for providing assistance with data analysis. Finally, we express our gratitude to Deborah Olson and Morgan Davis, Boise State University, for assistance with data entry.

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