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Using Guiding Questions to Promote Scientific Practices in Undergraduate Chemistry Laboratories

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ABSTRACT: Engaging students in scientific practices has become an important pedagogical component in STEM education, although its implementation in laboratories is still emerging. This paper uses three types of guiding questions to facilitate scientific practices in introductory and analytical chemistry laboratories. What makes our instructional model different from other developments is that certain types of scientific practices can be promoted by incorporating guiding questions into traditional laboratories, namely, type I prelaboratory questions for experimental design and implementation, type II postlaboratory guiding questions for knowledge construction, and type III postlaboratory guiding questions for experimental error analysis. Answers to these guiding questions were assessed for students' correct chemical knowledge and procedure design (type I) and for their presentation of the three key components of an argument: evidence, justifications, and claims (types II and III). A significant improvement in student score on types II and III questions and a modest upgrading on type I questions were observed as students progressed through Introductory Chemistry Laboratories to Analytical Chemistry Lab. Type I prelaboratory guiding questions incorporate a higher level of inquiry than types II and III postlaboratory guiding questions, thus more practices are needed to master advanced skills. Student performance on guiding questions improved throughout the semester in analytical chemistry laboratories. Students rated their experiences and helpfulness of guiding questions positively. This instructional model can be adopted in other science laboratories for setting up explicit goals and prioritizing useful information without changing the structure of curricula.

KEYWORDS: *First-Year Undergraduate/General, Upper-Division Undergraduate, Laboratory Instruction, Communication/Writing, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making*

INTRODUCTION

Shift from Broadly Defined Inquiry Activities to Clearly Itemized Scientific Practices

Equipping students with critical thinking skills through inquiry activities often serves as an important goal for higher education, though different definitions of critical thinking apply across the whole spectrum of subjects taught in college curricula.[1,2] Rogers raised concerns in the 1940s about the lack of transformation of science knowledge gained in science courses into other undergraduate studies or life experiences and suggested that more time should be given to students to practice scientific investigations and arguments.[3] Schwab pointed out in 1960 the urgent need in teaching science as inquiry and identified the laboratory setting as the best model for initiating inquiry.[4] Inquiry-based laboratory instruction improves training for STEM undergraduates due to its potential impact on a large number of students,[5] scenarios of student-centered environments and authentic problem-solving processes,[6] rich benefits in learning laboratory techniques, problem-solving ability and scientific thinking, etc.[7] The uniqueness of the laboratory setting lies principally in providing students with opportunities to engage in the processes of investigation. Nonetheless, educators have questioned the effectiveness and the role of laboratory work since the 1970s. The National Science Teachers Association published its series "What Research Says to the Science Teacher" in 1978. One of its chapters focused on the role of laboratories in secondary school science programs, in which Bates reviewed 82 studies and could not conclusively find what the laboratory accomplished that could not be superseded by other cheaper and quicker alternatives.[8] Tamir reported in 1983 that laboratory teaching was, in fact, not done in a way practiced by scientists.[9] Galloway and Bretz recently indicated that chemists faced the challenge of demonstrating that learning in the laboratory is complementary to, yet different from, learning outside the laboratory.[10] The latest Next Generation Science Standards (NGSS) for K−12 science education recommended eight scientific practices to reflect the way that scientists work, which go beyond the traditional focuses of content knowledge and skill development:[11] (1) asking questions, (2) designing and

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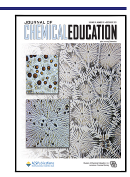

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using models, (3) planning and carrying out investigations, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) developing explanations, (7) engaging in argument and (8) obtaining, evaluating, and communicating information. This NGSS framework provides a vision not only for K−12 science education but also for college STEM learning.[12] In particular, a movement from science involving broadly defined inquiry activties[13] to clearly itemized scientific practices[11] provides the potential to improve the design and assessment of laboratory learning goals. The rubric of Educators Evaluating the Quality of Instructional Products (EQuIP) was designed to identify high-quality materials associated with NGSS[14] and was used as a guide for NGSS alignment.[15] Laverty et al. developed the Three-Dimensional Learning Assessment Protocol (3D-LAP) to characterize and support assessments of college science including biology, chemistry, and physics.[16] The modified 3D-LAP has been used to evaluate pre- and postlaboratory questions[17] and scientific practices in undergraduate chemistry laboratories, demonstrating that project-based laboratories show the potential for students to engage in scientific practices.[18]

Improvement of Critical Thinking Skills through Scientific Practices at Different Inquiry Levels

Students are less likely to generate critical thinking skills by learning theories than by hands-on practice. This practice should be deliberate and repeated with targeted feedback.[19,20] Holmes et al. argued that the key element for developing critical thinking ability is repeated practice in making decisions on the basis of data, with feedback on those decisions.[21] They found that students who were given more opportunities to acquire and interpret data in physics laboratories were more likely to identify limitations in their experimental methods and to improve them. Similarly, by evaluating student performance on precision and accuracy presented in laboratory reports, we found that the repetition of concepts and instructors' feedback are essential in constructing knowledge.[22] In the past, as well as today, content knowledge has formed the foundation of lecture curricula, while laboratories are designed to reinforce the concepts learned in lectures. Buck, Bretz, and Towns developed a rubric to assess the degrees of student independence in undergraduate science laboratories (confirmation level = 0, structured inquiry level = 1/2, guided inquiry level = 1, open inquiry level = 2, and authentic inquiry level = 3).[23] They evaluated 386 experiments in astronomy, biology, chemistry, geology, physical science, physics, and meteorology and found that the vast majority were highly structured to be level 0 or level 1/2. Such a laboratory setting, however, is being challenged by the measurements of effectiveness of laboratory instructions. Brederode and co-workers reported that high school seniors' critical thinking in organic chemistry laboratories was strongly influenced by the design of prelaboratory activities.[24] They found that students who started by developing experimental plan were more motivated to think deeply about their measurements than students who were given sensemaking preparatory questions. By comparing student performances in physics laboratories that emphasized experimentation skills to those that reinforced content learning, Smith et al. found no measurable difference in examination scores between these two laboratories but significant improvement in engaging students in expert-like experimentation in the laboratory that emphasized experimentation.[25] Rodriguez and Towns modified their existing laboratory curriculum with different pre- and postlaboratory questions,[17] providing a practical way to engage students in scientific practices. Similar effort was also made to improve teaching and learning by converting confirmation experiments into inquiry ones through guided constructivism[26] and data interpretation and hypothesis testing.[27]

Scientific argumentation engages students in constructing their own knowledge and justifying claims,[28] thus fostering critical thinking.[29] A strong argument should use evidence-based, relevant, specific, and accurate justifications to support the claim,[30] namely, including three key components (evidence, justification, and claim) in an argument. This ability is crucial for carrying out any investigations. Developing scientific arguments from evidence has been recommended by NGSS[11] and identified as an emerging focus in undergraduate chemistry curricula[31,32] and an essential competence for biology and physics education.[33,34] Supportive justifications for arguments may consist of numerical data (e.g., pH, mass, concentration, yield, temperature, absorbance, etc.) or observations (e.g., changes in color, temperature, phase, etc.). It is known that explicit expectations for students[35] and classroom practice[36] help develop an argumentative ability, while the lack of practice and instructional skills in organizing argumentative discourse impedes student progress.[36] Instructional models have been developed to guide students through the entire investigation process in a chemistry laboratory. The argument-driven inquiry (ADI)[31,37−39] and scientific writing heuristic (SWH)[40−44] are the two successful stories among them. Both ADI and SWH emphasize collaborative learning and scientific writing. ADI maintains a theme over several weeks and engages students in prelaboratory exercises, investigations, and claim construction for peer review and critique.[31,37,38] By examining students' laboratory reports in ADI classes, Sampson and Walker found significant improvement in students' ability to write science reports and evaluate the quality of peers' writing.[39] SWH supports learning by using an inquiry-based laboratory report format that directs students to answer questions, make a claim about what has been learned, and provide evidence to support that claim.[40] Very recently, SWH was also modified to support NGSS-aligned instruction.[45]

Nonetheless, the transformation toward scientific practices in laboratories is inhibited by various factors, such as a professional culture that favors research over teaching,[46] different levels of students' abilities and learning styles, traditional cookbook-style settings, and ingrained assessments focusing on contents and skills rather than the investigation processes. In particular, practical instructions for developing argumentative ability are still emerging.[47] More effective and flexible pedagogies would be helpful for both students and instructors. We herein use three types of guiding questions to introduce scientific practices into the existing laboratory curricula of Introductory Chemistry I and II (Chem. I and II Laboratories) and Analytical Chemistry (Anal. Chem. Lab). Those guiding questions were initially written by the instructors for their individual classes and then categorized into three groups. All questions emphasize the investigation processes based on students' own results, namely, type I prelaboratory guiding questions for experimental design and implementation, type II postlaboratory guiding questions for knowledge construction, and type III postlaboratory guiding questions for experimental error analysis. What makes our instructional model different from other developments is that certain types of scientific practices can be promoted by incorporating guiding questions into traditional laboratories. The guiding questions were designed to isolate specific skills for

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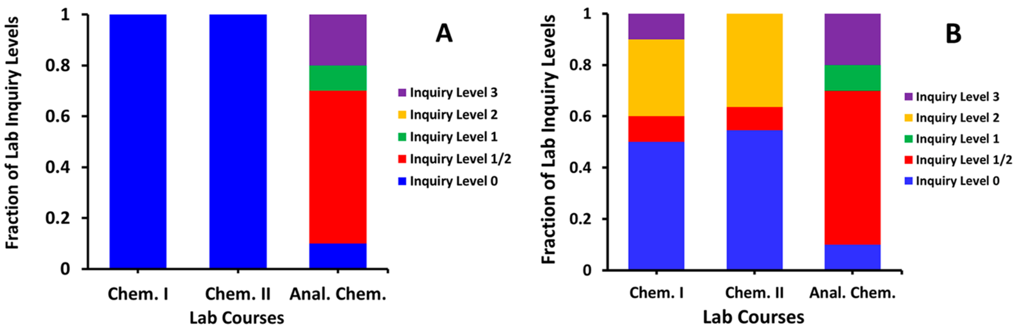

Figure 1. Inquiry levels of the laboratory experiments in each course in comparison of (A) before fall 2016 to (B) spring 2020.

concentrated practice and to gradually release learning responsibility to students for more efficient learning.[48] For instance, instructors can use type I prelaboratory questions to promote planning and carrying out investigations by simply changing the objectives and eliminating procedures or add types II or III postlaboratory questions to a confirmation laboratory to enhance inquiry activities. Student learning throughout different courses and during semesters in Anal. Chem. Lab was measured by instructors' grading of guiding questions and observations in laboratories, as well as students' own perceptions. This paper discusses the design, application, and assessment of these guiding questions.

DESCRIPTION OF PARTICIPATING LABORATORY COURSES

Guiding question-induced scientific practices have been carried out in the Chem I and II Laboratories and Anal. Chem. Lab at SUNY College at Old Westbury since fall 2016. All laboratory courses are offered in conjunction with corresponding lecture classes. To help students understand how lectures and laboratories are relevant to each other, the experimental schedules align with lecture sequences as much as possible. Most of the experiments are performed after students learn the necessary chemical concepts and principles in lectures. The laboratory classes of up to 24 students meet weekly for 3 (Chem. I and II Laboratories) or 4 (Anal. Chem. Lab) hours. With the support of the NSF-IUSE program between fall 2016 and spring 2020, many inquiry components were added to Chem. I and II Laboratories (∼50% as shown in Figure 1). The inquiry levels of the laboratory experiments were characterized using the rubric developed by Buck, Bretz, and Towns.[23] This rubric analyzes laboratory experiments used in high school or undergraduate science courses, aiming to connect the inquiry levels (e.g., structured, guided, open and authentic) to student independence and autonomy. It is worthwhile to mention that all of our chemistry laboratory courses contain some lower- or zero-level inquiry activities. These are still effective for introducing basic concepts. Activities with mixed levels of inquiry can better adjust to the diverse student population and maximize their learning. For most of the laboratories, instructors need to make a connection between students' prior knowledge and new materials being presented during prelaboratory lectures. A question-initiated dialogue between instructors and students is often a good way to introduce guiding questions, stimulate critical thinking, and make the objectives of the upcoming activities explicit. Students are allowed to work individually or in a group of 2−4 people of their own choice. The laboratory reports submitted by individual students or by groups are graded equally. When working in a group, each individual is responsible for writing certain sections of a laboratory report including Objective(s), Introduction, Procedure, Results, Discussion, Guiding Questions, Conclusion(s), and Safety Considerations. Alternatively, one group member may write an initial draft and share it on Blackboard for peer-review by other group members.

DESCRIPTION OF GUIDING QUESTIONS

Guiding questions were designed to draw students' attention to a specific area. They were used whenever possible to add inquiry features into existing laboratories. Since the publication of Bloom et al.'s taxonomy in 1956,[49] there have been extensive taxonomy versions of learning.[50] On the basis of a revised Bloom's taxonomy, Jensen and co-workers examined the effect of test question levels on fostering student conceptual understanding in an introductory biology course,[51] where all students were taught in a high-level inquiry-based style but evaluated in two groups, one given low-level questions (memory oriented) and another high-level questions (application, evaluation and analysis). They found that high-level questions encouraged not only a deeper processing of the information by students but also better memory for the core information.

The process of developing guiding questions was emergent and instructor driven. Specifically, faculty who taught in the participating laboratory courses attended a workshop to discuss scientific practices and how to promote them with guiding questions. A guiding question should encourage students to use their own experimental results toward the development of new knowledge. Faculty independently developed their guiding questions and determined how those questions would be included in either pre- or postlaboratory activities. The research team compiled the guiding questions and classified them into three categories based on which scientific practice they addressed. As such, not all scientific practices were addressed by guiding questions, which is not surprising given that the questions were incorporated into existing laboratory experiments in a limited number of laboratory courses. Answers to these guiding questions were assessed for students' correct chemical knowledge and procedure design (type I) and for their presentation of the three key components of an argument: evidence, justifications, and claims (types II and III).[30,52,53] Students need to support their justifications and claims with all possible evidence (data and observations) collected in experiments. It is possible to integrate more scientific practices into a confirmation laboratory, e.g., engaging students in "designing and using models" with the aids of free simulation tool of PhET[54] though that is not the focus of this paper. Guiding questions can serve as a bridge for students to transition from scientific practices to a more authentic research process. The main scientific practices and examples of guiding questions are

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provided in Table 1. A grading rubric and a comprehensive comparison between a confirmation laboratory and its modification are provided in the Supporting Information.

Type I guiding questions are prelaboratory assignments that are often associated with level 2-open inquiry laboratories, as defined by Bruck, Bretz, and Towns' rubric, in which the problem and background are provided but the procedure design, data collection, and result analysis are for the student to work out.[23] This type of guiding question sets up explicit goals to examine ones' own design or protocols, data, and observations. When using type I questions, instructors usually need to change objectives and eliminate procedures in laboratory instructions. As an example, calculating solution concentration with appropriate units is challenging for many undergraduates. Example 6 in Table 1 asks students to prepare their own standards and unknowns from solid chemicals or concentrated solutions. Students determine the mass to be weighed, volumetric tools, dilution factors, and calibration methods to be used, and concentration units needed to compare an experimental value to a theoretical one or true value. It normally takes half of the class time for students enrolled in Anal. Chem. Lab to do calculations and prepare solutions. We frequently use this type of guiding question in laboratories to improve students' understanding of stoichiometry and chemistry-related mathematics. In example 3 in Table 1 (as well as in the handouts given in the Supporting Information), students design a procedure to determine the molar absorptivity of ferrous thiocyanate ($FeSCN^{2+}$) with Fe^{3+} as a limiting reagent. They have learned the concepts of Beer's law, limiting reagents, and equilibrium constants in a traditional laboratory where they determined molar absorptivity with SCN^- as a limiting reagent. The different observations in color development and complex stability from these two protocols also provided the basis for deep thinking and error analysis.

Types II and III guiding questions are postlaboratory assignments that tend to align with guided or structured inquiry experiments in which students analyze results and experimental errors and derive conclusions on the basis of their own data and/or observations. These two types of guiding questions can be used in any laboratories whenever it is appropriate. Type II guiding questions focus on knowledge construction and are designed to bridge the gap between experimental results and textbook knowledge. Students are not expected to write a thorough review of concepts or principles; rather, they should prioritize information linked to objectives and their own data and observations. In example 2 in Table 1, students enrolled in Chem. I Lab were asked to explain why HCl was a stronger acid than CH_3COOH. Although much evidence could be supportive, there were only two relevant observations among others in their experiments: HCl reacted with metals (Zn, Mg, etc.) faster than CH_3COOH did, and the HCl solution had a lower pH than CH_3COOH at the same concentration. A similar exercise is given in example 4 in Table 1 where students summarize LeChatelier's Principle only on the basis of their observation. Type II guiding questions provide students with opportunities to analyze results and derive conclusions on the basis of their own data and/or observations.

Type III postlaboratory guiding questions are designed for any experiments involving replicate measurements and/or comparison of determined values to a known quantity (theoretical or true value). Background knowledge, such as precision and accuracy, random and systematic errors, as well as their evaluations in terms of standard deviation and bias, is

Table 1. Characteristics and Examples of Guiding Questions in Chemistry Laboratories

Guiding Questions	Type I Prelab Questions	Type II Postlab Questions	Type III Postlab Questions	Laboratories
Main scientific practices	Planning and carrying out investigations	Developing explanations, and engaging in argument	Analyzing and interpreting data and engaging in argument	
Grading	Correct chemical knowledge and procedure design	Presentation of evidence, justifications and claims	Presentation of evidence, justifications, and claims	
Example 1. Qualitative analysis	Design a flowchart to separate and identify Ni^{2+}, Fe^{3+}, Al^{3+}, and Zn^{2+}.			Chem. I
Example 2. Acids, bases, and salts		Why is HCl a stronger acid than CH_3COOH?		Chem. I
Example 3. Determination of ε for $Fe(SCN)^2$	Design an experimental procedure to determine ε with Fe^{3+} as limiting reagent.	Examine initial moles of reactants and moles of each species at equilibrium. Explain limiting reagent with your own data.	Compare molar absorptivity values determined from two protocols. If they are different, discuss why.	Chem. II
Example 4. LeChatelier's Principle		Summarize LeChatelier's Principle based on your results		Chem. II
Example 5. Any laboratories with known true values			Compare your result to the true value and discuss what made it higher or lower.	Chem. I and II, Anal. Chem.
Example 6. Any measurement laboratories	Design procedures to prepare standards, calibration curve, and unknown solutions. Show calculations!		Evaluate the precision with standard deviation and/or accuracy with bias when possible.	Anal. Chem.
Example 7. Penny statistics		Does the mass distribution of pennies follow a Gaussian distribution?	Are there significant differences in mean and in SD between different groups of pennies?	Anal. Chem.

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necessary for students to carry out measurements and analyze experimental errors. A density training laboratory for conceptual learning is held early in Chem. I Lab and Anal. Chem. Lab, where students use the known density and measured mass of water to calibrate micropipettes and volumetric glassware including beakers, volumetric flasks, and transfer pipettes.[22] These exercises equip students with concepts necessary for constructing their own error analysis (e.g., in spectrophotometric determination of Cu^{2+}, EDTA titration of Ca^{2+}, standardization of NaOH and HCl) in the future whenever it is needed.

■ ASSESSMENTS OF GUIDING QUESTIONS

Student Performances

Student performance on three types of guiding questions over a period of four years is given in Figure 2. Anal. Chem. Laboratories were taught by one instructor, while Chem. I and II Laboratories had multiple instructors with the data collected mainly by two instructors. Interrater-reliability analysis using Cohen's κ Statistic was, therefore, performed to evaluate consistency between raters for Chem. I and II Laboratories. Fifteen guiding questions (5 from each type, $5 \times 3 = 15$) were graded for satisfactory (= 1) or unsatisfactory (= 0) grading. The κ statistic value was found to be 0.73, showing substantial agreement between raters (Supporting Information). A similar improvement trend is seen on types II (orange bars) and III (gray bars) postlaboratory guiding questions with the percent correct answers increasing from 56.4% in Chem. I Lab to 64.1% in Chem. II Lab to 86.3% in Anal. Chem. Lab for type II guiding questions and from 70.2% in Chem. I Lab to 75.3% in Chem. II Lab to 83.1% in Anal. Chem. Lab for type III guiding questions. Students' t tests on types II and III questions show a significant difference between each interval moving from Chem. I to Chem. II to Anal. Chem. Laboratories (Supporting Information). The types II and III guiding questions were graded on the basis of how students supported their claims with justifications and their own data/observations collected in laboratories, thus indicating students' mastery of scientific argumentation. Example 7 in Table 1 asks a type II question, "Does the mass distribution of pennies follow a Gaussian distribution?". The answer may be yes if the graph made with students' data shows a characteristic Gaussian distribution or no if the number of mass values is too small. It would, however, indicate a misunderstanding about a set of measurements and different groups of measurements if students' analysis is based on a distribution plotted using the masses of all pennies composed of copper manufactured before 1982 and zinc coated with copper manufactured after 1982. More instructions in this area should then be provided to students in lecture or in laboratory, e.g., a classroom discussion about the difference in using students' t test for comparison of two means or one mean to the true value. Type II guiding questions promote learning patterns that move thinking from understanding to connection to construction, which is akin to the three basic epistemic actions in students' construction of mathematical knowledge: recognizing, building-with, and constructing.[55] Type III guiding questions require students to specify error sources rather than simply pointing out that there are human errors. A disagreement is often seen when comparing experimental results to the theoretical or true value. In example 5 in Table 1, students enrolled in Chem. I Lab were asked to specify the possible error sources in the measurement of molar mass. One group determined the molar mass of 1-hexene (M.W. = 84.15 g/mol) in three trials to be 41, 44, and 88 g/mol. They attributed the lower molar masses to the loss of 1-hexene vapor due to the prolonged evaporation (in trial 1) and delayed cooling time (in trial 2). An improvement was seen in the third trial when their laboratory skills were getting better. Another group obtained an average of molar mass 19.2 g/mol for acetone, which was much lower than the true value of 58.05 g/mol. Students learned through online searching that acetone had a low boiling point and weak intermolecular forces at room temperature, thus leading to a rapid evaporation and loss of vapors, subsequently resulting in a lower calculated molar mass than expected. Type III guiding questions encourage students to find out the reason behind each abnormal result and support their explanations and claims with data and observations collected in experiments. As students progress through introductory to advanced courses, they interpret experimental errors using standard deviation and bias. A combination of theory with practice moves error analysis from qualitative to quantitative levels (e.g., example 6 in Table 1).

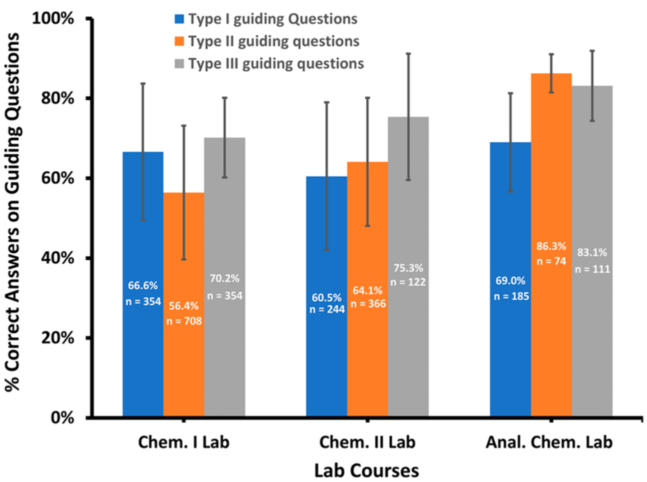

Figure 2. Instructor's average grading of type I postlab (blue bars), type II prelab (orange bars), and type III postlab (gray bars) guiding questions over four years between fall 2016 and spring 2020 in Chem. I Lab, Chem. II Lab, and Anal. Chem. Lab, n = #questions × #students (#students = 118 for Chem. I Lab, 61 for Chem. II Lab, and 37 for Anal. Chem. Lab). The error bars represent ± one standard deviation.

A modest improvement is seen when comparing student performance on type I prelaboratory guiding questions in Chem. II Lab to that in Anal. Chem. Lab, while there is no significant difference between Chem. I Lab and Anal. Chem. Lab with some decrease while moving from Chem. I Lab to Chem. II Lab. Type I prelaboratory guiding questions emphasize designing, planning, and carrying out investigations, which possess a higher level of inquiry activities than that promoted by type II and III postlaboratory questions. Students need more practice to master advanced inquiry skills and use them in investigations. In example 1 in Table 1, students in Chem. I Lab need to design a flowchart to identify one of the ions among Ni^{2+}, Fe^{3+}, Al^{3+}, and Zn^{2+} prior to coming to class. They have to review the chemical and physical properties of these ions and figure out how to detect them with the chemicals available in laboratory. Experimental design and execution were very challenging for many freshmen although they had learned theories in lecture classes. Instructors might have provided students with hints, e.g., an example of flowchart with irrelevant substances, which could have attributed to the higher scores on type I questions in Chem. I Lab rather than in Chem. II Lab.

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The guiding questions and inquiry levels of Anal. Chem. Lab have not changed much (Figure 1) for the past four years although the contents of each laboratory have changed. The relatively stable setting allows us to monitor students' progress throughout the semesters. As shown in Figure 3, students'

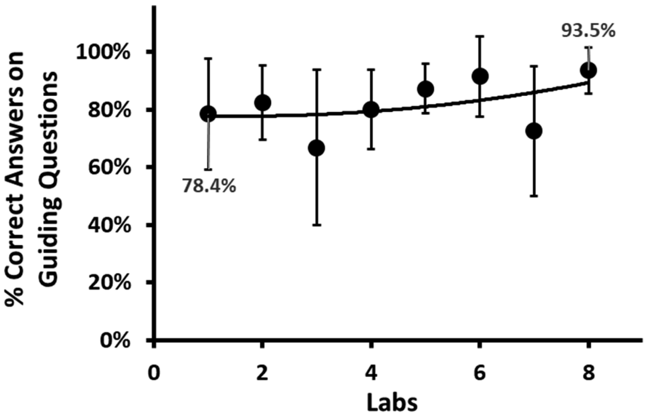

Figure 3. Overall grade distribution on three types of guiding questions in Anal. Chem. Lab with Lab 1 being conducted at the beginning of and Lab 8 at the end of semesters in fall 2017−2020. The error bars represent ± one standard deviation calculated with over 300 questions for a total of 37 students.

overall performance on guiding questions gradually improved with the percent correct answers increasing from 78.3% at the beginning of the semester (Lab 1) to 93.5% at the end of the semester (Lab 8).

Instructors' Observation and Students' Perception

A noticeable change with inquiry activities was that group members tended to spend more time together on calculations, discussion, and/or experimental replications, as needed. This observation is in line with the literature report where students in the experimentation laboratories spent significantly more time in class (mean ± SD = 118 ± 4 min) than students in the content-reinforcement laboratories (91 ± 7 min).[25] Multiple factors might influence students' behaviors, such as more time demand for inquiry activities, individual responsibility for writing certain part of a laboratory report, or answering guiding questions. When students take on the role of investigators and examine their own data or observations, the discussion in laboratory reports is more meaningful and deep thinking occurs. We observed the products of student's efforts in their written laboratory reports when they presented results in a way that explained a trend, a relationship, or an observation.

Postlaboratory questionnaires were distributed at the end of each semester. We provided no incentive for students to answer this voluntary survey. Students commented on guiding questions and scientific argument in several survey questions, as indicated in the questionnaires in the Supporting Information. Their responses show that they were engaged in those laboratory exercises. Students appreciated the opportunities for "enriched learning experience, (Chem. I Lab)", working on guiding questions for obtaining "better understanding of the material (Chem. I Lab)", and "a lot of experience in doing the calculations involved with determining the amounts of reagents to be used to complete many useful analytical chemistry methods (Anal. Chem. Lab)". Many students identified calculations and data analysis as a difficult part to follow while "the math for calculations in chemistry (Anal. Chem. Lab)" and "how to present and analyze data and calculations obtained from an experiment (Chem. II Lab)" were the skills they gained in laboratories. When students were asked what had been learned and would be carried into future studies, argumentative skills were among the gains achieved: scientific reasoning skills (Chem. I and II Laboratories), ability to discover or prove a scientific question by creating one's own experiment (Chem. II Lab), what to look for to determine if results will be acceptable and always questioning the purpose of each experimental step (Anal. Chem. Lab), how to properly write chemistry laboratory reports that reflect the experimental data collected (Chem. II Lab), how to efficiently manage time (Chem. I Lab), and being more careful and considerate in doing experiments (Anal. Chem. Lab). We also evaluated the students' view of guiding questions on an end-of-semester survey. Students were positive about the helpfulness of those guiding questions, providing average ratings on a 1−5 scale of 3.7 for Chem. I Lab (n = 175), 4.1 for Chem. II Lab (n = 74), and 4.2 for Anal. Chem. Lab (n = 13).

■ LIMITATION OF THE STUDY

SUNY OW is a small, minority-serving liberal arts college. A limitation of our study could result from the small student population and large percentage of transfer students. Approximately 50% of students in Chem. I Lab continued to Chem. II Lab, 30% from Chem. Laboratories to Anal. Chem. Lab; thus, the data described here is not for a defined cohort of students. The student perceptions about the helpfulness of guiding questions are based on questionnaire responses, which might only reflect the opinions of a certain group of students. In addition, the evaluation of student performance varies as guiding questions change. The results of this paper should be interpreted qualitatively.

■ CONCLUSIONS

Guiding question-modified laboratories promote learning throughout not only semesters as shown in Anal. Chem. Lab but also college years. As students progressed through introductory to advanced chemistry laboratories, their abilities in knowledge construction introduced by type II postlaboratory guiding questions and experimental error analysis introduced by type III postlaboratory guiding questions were greatly enhanced, while a modest improvement was observed with the use of type I prelaboratory guiding questions for experimental design and implementation. Type I questions initiate a higher level of inquiry activities than those introduced by types II and III questions, thus more practices are needed to develop skills. These guiding questions set up explicit goals for students and provide instructors with the freedom to modify their own curricula. Students commented and rated guiding questions positively. Further investigation is required regarding the impact of guiding questions on students' mastery of new knowledge that has not been covered in lectures.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00003.

Rubric for guiding questions, a list of postlaboratory survey questions, and handout examples of a confirmation laboratory and its modification (PDF)

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Statistical analysis of student's t test and Cohen's κ test (XLSX)

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Notes

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