JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

Development, Implementation, and Analysis of a National Survey of Faculty Goals for Undergraduate Chemistry Laboratory

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Supporting Information

ABSTRACT: This work reports the development of a survey for laboratory goals in undergraduate chemistry, the analysis of reliable and valid data collected from a national survey of college chemistry faculty, and a synthesis of the findings. The study used a sequential exploratory mixed-methods design. Faculty goals for laboratory emerged across seven factors, four of which—research experience, group work, error analysis, and laboratory writing—showed significant differences by course type. Significant differences between goals were also discovered when analyzed by external funding for the laboratory versus no funding. Synthesis across the previously published qualitative study and the quantitative study reported herein yields areas of emphasis in the curriculum for specific goals. This work adds weight to the growing body of global literature that implores faculty to define and assess their goals for laboratory.

What are our faculty goals for the undergraduate chemistry laboratory?

KEYWORDS: *First-Year Undergraduate General, Second-Year Undergraduate, Upper-Division Undergraduate, Chemical Education Research, Laboratory Instruction, Hands-On Learning/Manipulatives, Laboratory Management, Student-Centered Learning*

FEATURE: Chemical Education Research

■ INTRODUCTION

Science is based upon observations collected in the laboratory or the field, and thus laboratory experiments have become an established part of the undergraduate curriculum. Laboratory as a part of the chemistry curriculum has been explored and debated for years.[1−14] Nearly all faculty agree that laboratory is a vital component of the chemistry undergraduate curriculum; however, the explicit articulation of goals and aims within the literature is vague.

Research and literature from around the world have called into question the goals and aims of the laboratory. In a special issue of *Chemistry Education Research and Practice* (*CERP*) pertaining to learning in the chemistry laboratory, Reid and Shah wrote (ref 12, pp 173−174):

> *Laboratories are one of the characteristic features of education in the sciences at all levels. It would be rare to find any science course in any institution of education without a substantial component of laboratory activity. However, very little justification is normally given for their presence today. It is assumed to be necessary and important.*

One might hope that if laboratory were "assumed to be necessary and important", then the learning gains from the laboratory would be easily demonstrated. However, Hofstein and Mamlok-Naaman[11] in the same issue of *CERP* called attention to the lack of evidence in this regard (ref 11, p 106):

> *Many research studies have been conducted to investigate the educational effectiveness of laboratory work in science education in facilitating the attainment of the cognitive, affective, and practical goals. These studies have been critically and extensively reviewed in the literature. ...[F]rom these reviews it is clear that in general, although the science laboratory has been given a distinctive role in science education, research has failed to show simple relationships between experiences in the laboratory and student learning.*

If the relationship between experiences in the laboratory and student learning remains obscure, then one arrives at the provocative statement composed by Rice, Thomas, and O'Toole[13] in their review of tertiary science laboratory in Australia (ref 13, p 13):

> *The most important issue in the context of laboratory classes is whether there needs to be a laboratory program at all.*

Although laboratory is a well-established, nearly unassailable element of the chemistry curriculum what the laboratory experience helps students learn remains an open question.

■ THE NEED FOR GOALS IN THE LABORATORY

Reid and Shah[12] reviewed the literature on laboratory, identifying four aims for laboratory work (p 178):

1. *Skills relating to learning chemistry*: Making chemistry real by illustrating ideas and concepts, exposing theoretical ideas to empirical teaching and teaching new chemistry.

Published: April 1, 2013

2. *Practical skills*: Handling equipment and chemicals, learning safe scientific practices, mastering specific techniques, measuring accurately, and observing carefully.
3. *Scientific skills*: Learning the skills of observation and the skills of deduction and interpretation. Appreciation of the place of the empirical as a source of evidence in inquiry. Learning how to devise experiments that offer insights into chemical phenomena.
4. *General skills*: Numerous useful skills to be developed such as team working, reporting, presenting, discussing, time management, and problem-solving skills.

As Reid and Shah[12] noted, these general aims have significant overlap. However, Boud, Dunn, and Hegarty-Hazel[15] argue (ref 15, p 8):

> *General statements of values and goals alone do not provide sufficient guidance for detailed course planning. They have to be translated into particular aims and objectives which describe what it is that students and others will do.*

Thus, there is a need to identify specific, measurable, achievable, and relevant goals that faculty hold for laboratory.

In 2005, we embarked on a research program to explore faculty perspectives of undergraduate laboratory, including their goals. On the basis of the findings of a qualitative study, in Bruck, Bretz, and Towns,[16] we described laboratory goals held by faculty at the course level, differentiated by funding, across the curriculum. Our next steps forward in this research program were to construct and validate a laboratory goals survey; to collect data from a national sample, analyze, and interpret the data collected; and ultimately to promote discussion about laboratory goals among college chemistry faculty.

■ SCOPE OF THE STUDY AND RESEARCH QUESTIONS

The purposes of the study were to

Develop a survey based upon the results of the qualitative study and ensure the reliability and validity of the data collected.

Use the survey to collect data from a national sample of college chemistry faculty to discern information about faculty goals for laboratory.

Promote a discussion among chemistry faculty about the goals for the laboratory curriculum.

The research questions that drive the analysis of the data include these:

How do faculty goals for chemistry laboratory differ by course, institutional type, and funding sources?

How do faculty goals for laboratory documented in the qualitative and quantitative studies compare to one another?

■ METHODOLOGY

This research is part of a larger study on faculty perspectives of undergraduate laboratory. It is guided and framed by a sequential, exploratory, mixed-methods design that requires both qualitative and quantitative data.[17] This research design is well suited to survey or instrument development in the circumstance in which no previous instrument exists. The design allows the findings from a qualitative study to be generalized to a broader population by developing a quantitative measure that is grounded in the qualitative data and findings.

To frame the genesis of the survey, the qualitative study will be described briefly. The focus of the study was to describe the faculty perspectives of undergraduate laboratory. The goals, curriculum, and assessments were the focus of the interview protocol. A stratified random sample was drawn from faculty at American Chemical Society (ACS)-approved chemistry departments at research, comprehensive, and liberal arts universities. Community-college faculty members who belong to the Two-Year College Chemistry Consortium (2YC3) were also included in the sample because the ACS does not approve community college chemistry programs. The sample included faculty who were specifically interviewed about general chemistry, organic chemistry, or upper-division laboratories. The sample was further stratified by those who had received NSF-Course, Curriculum, and Laboratory Improvement (CCLI) grants. Each transcript was coded individually, and then analyzed both across courses and across CCLI versus non-CCLI faculty. The results of the study have been described in the *Journal*.[16]

■ DEVELOPMENT OF THE FACULTY GOALS FOR UNDERGRADUATE CHEMISTRY LABORATORY SURVEY

The findings that emerged from the qualitative study guided the development of an instrument to examine the goals for undergraduate laboratory. By surveying a larger sample of faculty, we planned to further explore themes and tentative hypotheses that emerged from the qualitative study.

An initial pool of survey items was developed from findings of the qualitative study. Questions constructed from key interview themes asked respondents to identify the frequency of certain laboratory practices, such as conducting error analyses or writing formal laboratory reports. These items were scored on a five-point scale with options ranging from "0% of the time", marked as a 1, to "76−100% of the time", marked as a 5. A second type of survey item asked faculty to indicate their level of agreement or disagreement with statements pertaining to goals for laboratory practice. Responses to these statements ranged from "Strongly Disagree" to "Strongly Agree" across a six-point Likert scale. This arrangement of responses left no neutral response in the middle, thus forcing respondents to choose between agreement and disagreement. Demographic questions were also included in the survey to facilitate analysis based on institutional, course, and funding groups and comparison of the findings to the qualitative study.

The initial set of survey questions was reviewed and refined in order to create a pilot survey comprising 44 Likert-scale items, 15 questions that targeted frequency of use, and 15 demographic questions. A feedback section containing three free-response questions was added to the end of the survey for the purpose of gaining information about how the survey could be improved. The survey was entered into Qualtrics to facilitate online data collection.[18]

Pilot Study

The respondent pool for the pilot survey (N = 45) was composed of the faculty from the International Center for First-Year Undergraduate Chemistry Education (ICUC) and those involved in the ACS Examinations Committees for organic chemistry and upper-division courses. Faculty were invited via e-mail to participate in the study and complete the survey online.

The data were analyzed using correlation tables, Kaiser−Meyer−Olkin (KMO) tests, Cronbach's α, and factor analysis. Taken as an entire analytical approach, these tests allowed the researchers to discard items that had low correlation values, KMO values, or Cronbach's α values. Through this process, 17 of the Likert-scale items and 13 of the frequency items were discarded.

For the remaining 29 items (27 Likert scale and two frequency items), Cronbach's α was 0.856, which is above the minimum acceptable value of α = 0.700.[19] The factor analysis produced eight factors that related back to the original findings from the qualitative study. The Cronbach's α values for each individual factor ranged from α = 0.707 to α = 0.861. These measures suggested that each of the extracted factors from the pilot survey had a high level of internal reliability and the pilot survey itself had strong overall reliability.

The pilot study also included a free-response section to gather feedback from the participants about the content and structure of the survey. Similar to the panel of experts approach used by other researchers to ensure face validity,[20] this section addressed the validity of the instrument by allowing faculty to comment upon the ability of the survey to capture their goals for laboratory. It also improved the construct validity of the instrument by ensuring that it accurately reflected the construct of laboratory goals.

Full Study

Upon the basis of the pilot study, the full study was carried out with the "Faculty Goals for Undergraduate Chemistry Laboratory Survey", a 29-item survey, demographic questions, and a free-response question for participants to provide additional information or comments. To carry out factor analysis with reliable results,[21] we needed 145−580 participants (5−20 times the number of survey items). Thus, we adopted a sampling strategy to obtain the required number of participants while ensuring the sample was representative of the diversity of institutions across the United States.

Because of the density of colleges and universities with ACS approval in the eastern and midwestern United States (see Table 1), our sampling strategy needed to ensure that the sample achieved was not biased toward one region of the United States. Thus, the country was split into seven regions, using a modified regional scheme from the U.S. Census Bureau shown in Figure 1.[22] Using a random-number generator, 15 universities or colleges from each region were selected. Recruitment letters were e-mailed to the chair or head of each chemistry department at the selected universities and colleges. The URL for the online survey was included in the recruitment e-mail, and department heads were asked to invite faculty who were involved in teaching laboratory or in developing the laboratory curriculum to participate in the study. In cases where the list of teaching faculty was readily available online, e-mails were also sent directly to faculty members. In total, 1850 e-mail invitations were sent.

Table 1. Distribution of ACS-Approved Universities and Colleges per Sampling Region

Region in the U.S.	Number of Universities and Colleges
New England	53
Middle Atlantic	134
South Atlantic	97
Middle South	95
East North Central	120
West North Central	60
West	96
Total	655

Given that the ACS does not approve chemistry programs at community colleges, a different sampling methodology was used in order to ensure participation from a representative number of community-college faculty. In order to recruit community college participants, the e-mail list for the 2YC3 was obtained. The 805-member list was split into regions as shown in Figure 1. However, because the New England region only contained 14 members, e-mail invitations were sent to 14 faculty from each region to avoid having a majority of responses for a demographic group come from only one region of the country. Accordingly, a total of 98 invitations were sent to community college participants.

The online survey remained active for one month, from March to April 2009. During the data collection process, reminder e-mails were sent twice after the initial invitation to participate in the study. The total number of survey responses by institutional type and course is shown in Table 2.

■ DATA ANALYSIS

The survey responses were analyzed using correlation tables, Cronbach's α, Kaiser−Meyer−Olkin tests, and factor analysis, resulting in the seven factors and associated Cronbach α values shown in Table 3. The details of these analyses, including the factor loadings, are contained in the Supporting Information.

The Cronbach α value for the entire survey was 0.904, demonstrating high internal consistency for the instrument. The data were subsequently analyzed by course, institutional type, and funding status. Responses were grouped by course as follows: general chemistry, organic chemistry, analytical chemistry (second-year analytical and instrumental analysis), physical chemistry, and upper-division. Analysis by funding type was performed on three groups: those who had received external funding, those who had received internal funding (meaning support was obtained by faculty at their home institution), and those who had no funding.

The data set was analyzed for statistical and practical significance using ANOVA techniques, Tukey's HSD tests with α = 0.05, and Cohen's d for effect-size calculations. These analyses allowed us to determine differences in faculty goals for the chemistry laboratory by course, institutional type, and funding.

Analysis of Free-Response Question

The final question on the survey was designed to allow a larger number of faculty than those who could be interviewed in the qualitative study to comment upon their goals for laboratory. The question asked, "What additional information would you offer about your laboratory goals?" and was accompanied by a textbox. Responses to this question were grouped by course and were analyzed using the qualitative-data management software NVivo.[23] An open-coding[24] analysis approach was used, however the codes were shaped by the results from the qualitative study. Themes from this analysis were compared to the findings of the qualitative and quantitative studies to add further depth, nuance, and perspective to our interpretation of faculty's goals for undergraduate chemistry laboratory.

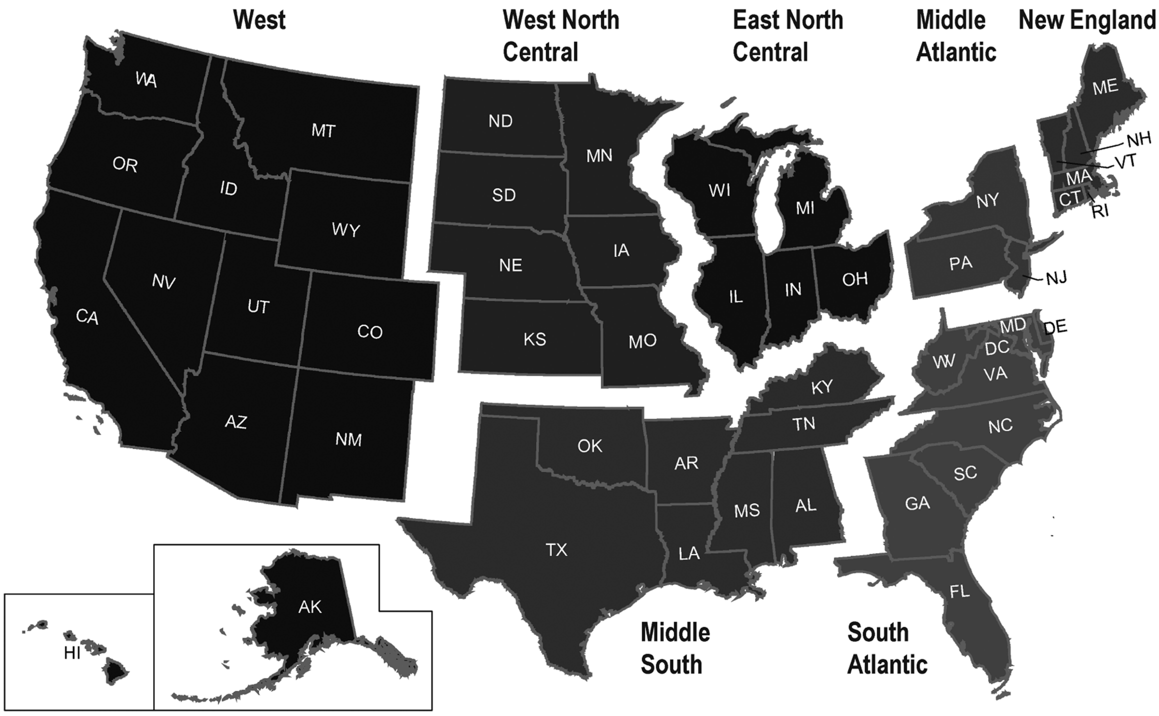

Figure 1. Regional sampling scheme modified from layout used by U.S. Census Bureau.[22] Not pictured is Puerto Rico, part of the South Atlantic region for the population.

Table 2. Responses by Type of Institution and Course

	Count, N			
Institutional Type	General Chemistry	Organic Chemistry	Upper-Division Chemistry	Total by Institution
Community college	26	9	1	36
Primarily undergraduate institution	38	29	61	128
Comprehensive university	11	6	11	28
Research university	34	27	59	120
Total by course	109	71	132	312

■ RESULTS AND DISCUSSION

Throughout the discussion that follows, both statistical significance and effect sizes are presented. While statistical significance is often noted in quantitative research, it indicates little about the *practical* significance of the outcome. Effect sizes complement significance tests in that they provide a measure of the difference between two means of interest in terms of the pooled standard deviation (the difference of the means divided by the pooled standard deviation). Thus, effect sizes are used to call attention to the practical significance of the work. These values give researchers and practitioners guidance on how to make decisions using the results. Cohen's d was used as the effect-size measurement and numerically the values correspond to the following descriptors: <0.2 is trivial, 0.2−0.49 is small, 0.5−0.8 is medium, and >0.8 is large.[25]

Analysis of Factors by Course

The factors shown in Table 3 were analyzed by course using an ANOVA, and statistically significant differences were found for four of the seven factors. A Tukey's HSD test was conducted using a p-value of 0.05 to identify which courses were significantly different within each of the four factors. The factors and the particular pairs of courses in which the comparisons found to be statistically significant (meaning $p < 0.05$) are presented and discussed below with accompanying effect-size values (Cohen's d).

Research Experience. General chemistry faculty rated goals associated with *research experience* significantly lower than faculty in all other courses, as shown in Table 4. A possible reason for this outcome is that general chemistry courses serve a broad population of students: future engineers, nurses, agricultural economists, and so forth. Thus, preparing students to engage in undergraduate research in a chemistry laboratory or mimicking research experiences are goals that may not be emphasized. Additionally, having students use instrumentation found in research laboratories or in industry may be cost prohibitive; that is, the resources to purchase multiple instruments for large enrollment courses may not exist.

The effect size for *research experience* is medium for the general chemistry versus organic chemistry laboratories, but it trends toward larger values for the comparisons between general chemistry and analytical, physical chemistry, and upper-division courses. This trend in effect-size values is reasonable given that this set of courses serves primarily chemistry majors and the goals would shift to emphasize laboratory techniques used by chemists in industry or in the research laboratory as majors progress through the curriculum.

Group Work. Organic chemistry faculty placed less emphasis on *group work and broader communication skills* than faculty in other courses. The priority of *group work* as a goal for the organic chemistry laboratory was significantly lower for organic versus analytical chemistry laboratories (p = 0.007, d = 0.65) and for organic versus physical chemistry (p = 0.037, d = 0.58), both demonstrating medium effect sizes. This outcome is consistent with the results of the qualitative study that demonstrated that faculty goals for organic chemistry laboratory are highly technique oriented. Thus it is likely that organic faculty placed more emphasis on individual students

Table 3. Factors and Corresponding Survey Items of the Faculty Goals for Undergraduate Chemistry Laboratory Survey

Survey Items by Factor[a,b]
Factor 1: Research Experience (α = 0.835)
Laboratory techniques used by professional chemists are used in the teaching laboratory.
Preparing students for research experiences is a goal for the laboratory.
The laboratory gives students an idea of how chemistry is performed in the real world.
The laboratory is designed to encourage the development of scientific reasoning skills.
Understanding the usefulness of specific laboratory techniques is a goal for the course.
How often are students conducting experiments that mimic research experiences?[c]
Factor 2: Group Work and Broader Communication Skills (α = 0.829)
Students need to learn to work together in laboratory to succeed in future courses.
Students need to learn to work together in laboratory to succeed in their future careers.
Group work in laboratory encourages students to use their peers as information sources.
This laboratory course is designed to develop oral communication skills.
The laboratory is designed to have students present data in multiple formats such as PowerPoint, posters, laboratory reports, etc.
Factor 3: Error Analysis, Data Collection and Analysis (α = 0.823)
Error analysis is necessary to understand the limitations of measurement in the laboratory.
Teaching students about uncertainty in measurement procedures is important.
Laboratory is a place for students to learn to analyze data.
Understanding the need for proper data collection techniques is a goal for laboratory.
How often are students required to carry out an error analysis?[c]
Factor 4: Connection between Lab and Lecture (α = 0.859)
Making laboratories relevant to lecture content is an aspect of our laboratories.
There is a strong connection between the lecture and the laboratory.
The goal for laboratory instruction is to reinforce lecture content.
Factor 5: Transferable Skills (Lab-Specific) (α = 0.805)
Laboratory activities and experiments selected for this course are designed to develop students' mastery of laboratory techniques.
Laboratory activities and experiments selected for this course are designed to focus on skills that are transferable to research-oriented laboratories.
Laboratory activities and experiments selected for this course are designed to develop skills that students can apply to future science courses.
Factor 6: Transferable Skills (Not Lab-Specific) (α = 0.669)
Laboratory activities and experiments selected for this course are designed to teach students to build logical arguments based on their data.
Laboratory activities and experiments selected for this course are designed to foster an appreciation for science in students.
Laboratory activities and experiments selected for this course are designed to generalize to multiple disciplines.
Factor 7: Laboratory Writing (α = 0.769)
Teaching students how to write scientific reports is a goal for laboratory.
Writing laboratory reports helps students to communicate what they know about chemistry.
Learning to keep a proper laboratory notebook is a vital skill for students to acquire.

[a]Participants (N = 312) responded to items using a six-point Likert scale that ranged from "strongly disagree" (1) to "strongly agree" (6). [b]For the entire survey, Cronbach's α = 0.904. [c]Frequency-item questions were scored on a 5-point scale ranging from 0% of the time (1) to 76−100% of the time (5).

Table 4. Significant Differences in Research Experience Compared by Course Listing p Value and Effect Size

Tukey's HSD Comparison[a]	p Values	d, Effect Size
GC vs Organic Chemistry	<0.001	0.59
GC vs Analytical Chemistry	0.001	0.75
GC vs Physical Chemistry	0.002	0.67
GC vs Upper-Division Chemistry	<0.001	0.93

[a]GC is general chemistry.

Table 5. Significant Differences in Error Analysis Compared by Course Listing p Value and Effect Size

Tukey's HSD Comparison	p Values	d, Effect Size
Organic vs General Chemistry	0.006	0.47
Organic vs Analytical Chemistry	<0.001	1.39
Organic vs Physical Chemistry	<0.001	1.19

mastering laboratory techniques and less emphasis on learning to work together in a group.

Error Analysis. Organic chemistry faculty placed less emphasis on goals pertaining to *error analysis, data collection and analysis* than did other faculty. The difference was significant for general chemistry, analytical chemistry, and physical chemistry faculty, as shown in Table 5. The effect size was small between organic chemistry and general chemistry courses. However, the values were greater than one for organic and analytical chemistry courses and organic and physical chemistry courses. We postulate that the large effect sizes emerged for a variety of reasons. First, physical chemistry courses generally emphasize error analysis in a formal way. Faculty may teach propagation of error techniques within the course and thus see it as a priority in terms of laboratory goals. Second, the analytical category contains instrumental analysis, a course that is typically taken by third- and fourth-year chemistry majors. Thus, the students have usually been exposed to propagation of error formulas in physical chemistry and use them in instrumental analysis. Third, in the qualitative study, the notion of identifying just how good a calculated value is via its uncertainty emerged as a goal in the upper-division courses (which in that study included instrumental analysis and physical chemistry).

dx.doi.org/10.1021/ed300371n | J. Chem. Educ. 2013, 90, 685−693

Laboratory Writing. General chemistry faculty placed less emphasis on *laboratory writing* than all other faculty, as shown in Table 6. The effect sizes vary between small and medium, but there seems to be some evidence that the effect size grows larger as students move through the chemistry curriculum from general to organic through analytical and physical chemistry.

Table 6. Significant Differences in Laboratory Writing Compared by Course Listing p Value and Effect Size

Tukey's HSD Comparison[a]	p Values	d, Effect Size
GC vs Organic Chemistry	0.026	0.39
GC vs Analytical Chemistry	0.009	0.57
GC vs Physical Chemistry	<0.001	0.78
GC vs Upper-Division Chemistry	<0.009	0.52

[a]GC is general chemistry.

These survey findings for *laboratory writing* are different from those learned through interviews in the qualitative study. In the interviews, the organic chemistry faculty described goals related to keeping good laboratory notebooks and developing reports, which other faculty did not. However, it seems that the quantitative results reveal a different perspective on laboratory goals. We believe that there may be an underlying issue in this factor related to the way laboratory writing is implemented in the general chemistry curriculum. In the qualitative study, faculty described "fill-in" worksheets being used in general chemistry. In some general chemistry curricula the data collection and analysis may be very directed as it would be in a traditional laboratory.[26] The development of hypotheses or research protocols may not be part of the general chemistry curricula in many institutions. Further, the generation of conclusions based upon experimental evidence, analysis of error, or relation of experimental observations and measurements to models may not be part of the writing required at the end of the laboratory. Thus, writing laboratory reports or learning how to keep a laboratory notebook depends upon the nature of the implemented curriculum and faculty goals for laboratory. Our data suggest that laboratory writing as a goal receives less emphasis in general chemistry than other laboratory courses.

Analysis by Institutional Type

The results of the survey were analyzed using the factor structure to determine whether there were differences by institutional type. No significant differences were found, which suggests uniformity in goals across institutional types. This was consistent with the findings from the qualitative study in which the goals were found to be indigenous to courses, but not to particular institutional types.

Analysis by Funding

The demographics section of the survey asked if participants had received external funding from any source, internal funding through their college or university, or no funding at all for the improvement of laboratories and laboratory instruction at their institutions. An ANOVA of factors by funding type showed significant differences at the $p < 0.05$ level for the factors *research experience,* $F(2{,}300) = 4.101$, $p = 0.018$; *error analysis,* $F(2{,}300) = 3.360$, $p = 0.036$; and *laboratory writing,* $F(2{,}300) = 0.369$, $p = 0.0.36$. For the entire survey, the analysis provided a p-value that approached significance: $F(2{,}300) = 3.001$, $p = 0.051$. A Tukey's HSD test for significance revealed significant relationships, as shown in Table 7.

Table 7. Statistically Significant Tukey's HSD Values and Effect Sizes for the Analysis of Factors by Funding Type

Factor	Tukey's HSD Comparison	p Values	d, Effect Size
Research experience	External vs Internal	0.035	0.369
	External vs No funding	0.039	0.356
Error analysis	External vs No funding	0.032	0.368
Laboratory writing	External vs No funding	0.046	0.357
All questions	External vs No funding	0.051	0.335

For each factor shown in Table 7, the faculty who received external funding had higher means than faculty who had received internal funding or no funding. In each case of significant difference, the effect size is small, less than 0.4. *Research experience* is the only set of goals that revealed a significant difference between external and internal funding sources. In every other case, including the entire survey, the only significant differences detected were those between the external and no funding groups.

Upon the basis of these analyses, we hypothesize that perhaps faculty who were able to obtain external funding emphasized laboratory goals pertaining to *research experiences, error analysis*, and *laboratory writing* differently than did faculty who received no funding. Although the effect size is small, the practical value of receiving funding from an external source in driving forward laboratory improvements via new instruments and revised curricula is substantial, especially if it affects a large number of students. Thus, one inference that can be drawn is that the most important types of laboratory goals to consider in drafting external proposals are those related to preparing students for research experiences, those that help students understand the uncertainty of measurements, and those that pertain to writing in the laboratory.

The funding groups in the qualitative study were parsed as external or not external, which included the "internal" funding group. In the quantitative study, we sought to separate out this group of faculty to account for differences that may have emerged due to internal funding mechanisms. Thus, general chemistry, organic chemistry, and all other upper-division courses were each analyzed by funding type—external, internal, and no funding—to discover whether there were significant differences in the factors by funding type. The analyses yielded no significant differences across funding types.

■ FINDINGS FROM THE ANALYSIS OF THE FREE-RESPONSE QUESTION

Replies to the free-response survey question allowing faculty to offer additional information about their laboratory goals permitted us to gain additional insight into the findings from the qualitative interviews and the quantitative survey. Analysis of these responses yielded categories pertaining to laboratory goals, as well as obstacles and challenges in implementing laboratory courses.

Complementary to the qualitative study, faculty across the curriculum wrote about the importance of students' learning laboratory skills and techniques. As one general chemistry faculty member wrote "teach[ing] lab techniques as a toolbox for solving problems" was a key goal for the course. Upper-division level faculty focused on exposing students to techniques:

We try to cover as many topics relevant to inorganic chemistry as possible, such as air-sensitive techniques, bio-inorganic chemistry, materials chemistry, organometallics, etc. One of the goals of the lab is to expose chemists to techniques that are common in biology labs, but which they might not have seen before.

Faculty also described specific laboratory approaches to carry out experiments. Organic chemistry faculty wrote of incorporating "green" chemistry practices into the curriculum with an emphasis on techniques. Faculty across the curriculum also discussed safety as a goal. This was framed both as a matter of knowing "safe procedures for handing all chemicals" and a matter of safely disposing of chemicals.

As in the qualitative study, faculty commented upon the importance of students' suggesting improvements to experiments and making choices in experimental protocols to engage in experimental design. Faculty in general chemistry and organic chemistry also discussed the importance of connecting lecture to lab:

I find that students don't always form a mental connection between the laboratory and lecture. I discuss concepts in lecture and the students seem to understand (based on classroom exams). However, when the same concepts are covered in the lab, they have to relearn the concept. When questioned, they usually respond that they didn't realize that the concepts were related.

At many institutions, general and organic chemistry are taught as integrated lecture laboratory courses. Both general and organic faculty members wrote about connecting lecture to the laboratory, in some cases emphasizing how laboratory activities could support the content learned in lecture.

The notion that laboratory work reinforces lecture concepts exists among faculty, but as Hofstein and Mamlok-Naaman have indicated, the relationship between conducting a laboratory and meaningfully connecting such activities to lecture concepts is not simple.[11] A recently published National Academy of Sciences report indicates that there is little evidence to support the widely held faculty belief that laboratory activities reinforce or enhance student understanding of concepts.[27] Research-based evidence of what students actually learn from engaging in laboratory activities would be extraordinarily helpful to faculty developing laboratory curricula and those who seek to maintain institutional resources devoted to laboratory.

In our interviews, faculty pointed to sources of frustration, including ill-prepared students, the ability of graduate teaching assistants to facilitate and assess learning, and the involvement and accountability of faculty in the laboratory curriculum.[16] In the quantitative study, the findings point toward obstacles and frustrations with the laboratory course that include high enrollment courses with diverse majors, the unchanging nature of the curriculum, and the balance between resources and responsibilities. Each of these difficulties is discussed in more detail below.

Large Enrollment Courses and a Broad Range of Majors

Faculty responsible for general chemistry and organic chemistry laboratory wrote about the challenges of courses with hundreds to over a thousand students, the majority of which are *not* chemistry majors.

About 460 students take the lab—many different majors!

The majority of the students are biology pre-PT/PA/BSRN, and geoscience majors.

Many, many of my students are pre-medical or pre-dental students who struggle to see the application of their chosen profession when I treat them like chemistry majors.

The goals at the organic chemistry level are less ambitious because we have a huge number of students who are pre-meds and won't ever do chemistry again.

Although faculty in most cases did not state how they addressed these challenges, two discussed "streamlining the method with which course content and grading are done" and the supervision of teaching assistants. These are ways in which faculty managed high-enrollment courses and the necessary training of teaching assistants to meet the goals of the course.

However, faculty did not indicate how they dealt with the breadth of majors in their laboratory courses, specifically the preprofessional majors. To address students oriented toward health science majors, two recent reports may be useful. *Scientific Foundations for Future Physicians*, and *MR5* encourage faculty who teach future physicians to adopt an approach that emphasizes relevance to the life sciences.[28,29] These two reports provide guidance for revising the curriculum for faculty who teach health or life science majors and "pre-meds" who may wish to understand how the chemistry they learn is relevant to their future professional goals. Faculty who face a broad range of majors may find that these reports provide information and recommendations worthy of adaption and adoption in their own curriculum and facilitate the articulation of laboratory goals.

A Static Curriculum

Faculty also expressed frustration over a curriculum that either has not changed over time or institutional factors such as time, resources, and institutional culture that hinder changes.

The current set of experiments has been carried out for at least 20 years and could be substantially improved.

It is a dysfunctional laboratory, using a lab manual...with experiments that haven't been changed in the 5 years I've been there. Students copy old pre-lab exercises from each other, and the TAs are comfortable grading the work, knowing full well that the work is not original. Oh, well—complaining doesn't do much good, and to redesign the entire curriculum is not on the horizon.

These faculty (and likely others) recognized that changing and improving the laboratory curriculum requires effort, commitment, and resources. Upon the basis of the findings of our qualitative study, we hypothesized that "NSF-CCLI (now TUES) grant recipients recognize that faculty input is required to improve laboratory curricula" (ref 16, p 1421). Across both studies, the findings suggest that some faculty see the NSF-TUES program as a way to facilitate the changes they seek in the curriculum and in their available instrumental resources. However, local institutional circumstances and inertia may hinder faculty members' ability to drive forward changes.

Decline in Resources and Increasing Responsibility

Respondents described frustrations with declining resources and increasing responsibilities and the feeling that the students are the ones who suffer from a poorer learning environment:

My responsibilities include all undergrad laboratory courses up to and including organic, physical, environmental, analytical, inorganic, and instrumental. However, my participation is limited due to these courses involving near 600 students total in any given year. ...I must constantly strive to be as prepared and organized as possible, as these are prerequisite for adequate attention being given each student.

Our lab program is a MESS. The lab assignments are poor, our facilities are worse. [General chemistry] lab is often not offered due to space and time constraints. ...I do lab prep this semester just to insure that something is done correctly. We are REALLY letting our students down with the current lab structure and it makes me sick!

The resources faculty referred to included time, facilities, and money to support maintenance or improvement of laboratories. As those resources decline and faculty (or staff) responsibilities increase, the effect can be deleterious to departmental culture and the undergraduate curriculum.

■ SYNTHESIS ACROSS THE QUALITATIVE AND QUANTITATIVE STUDIES

The sequential, exploratory, mixed-methods research design of this project allows for the integration and synthesis of findings across the qualitative and quantitative studies to produce a broader, deeper, and more nuanced understanding of faculty goals for laboratory. Here, we synthesize our emergent findings from the qualitative study with the findings from the national survey, focusing on the factors that produced statistically significant results.

In the quantitative study, the *research experience* factor corresponds to an emphasis on *critical thinking* and *experimental design* from the qualitative study. The latter found common ground across all courses; however, the survey detected a greater emphasis on these goals in courses beyond general chemistry. The combined data suggest that as students, especially chemistry majors, move through the curriculum, faculty increasingly emphasize laboratory techniques used in research laboratories and industry. Further, there is an emphasis on understanding what the techniques are used to do and how the data is analyzed and interpreted.

The goal of learning to work with others, defined as the *group work* factor in the quantitative study and the emergent theme of *teamwork* in the qualitative study, produced varying results across the studies. The survey highlighted the lack of emphasis on *group work* by faculty in organic chemistry, and it is likely that this finding is tied to the technique-driven nature of the curriculum. While faculty in general chemistry discussed teamwork skills in the qualitative study, this goal did not emerge in other courses.

Error analysis, or developing an understanding of the uncertainty of measurement, was a goal strongly tied to upper-division courses in the qualitative study that included physical chemistry and instrumental analysis. Results from the survey suggested that the goal was less important in organic chemistry, but the effect sizes between organic and physical chemistry and organic analytical were both large—greater than 1.0. Both studies converge on the finding that understanding the uncertainty in measurement and how such uncertainty influences data interpretation is a paramount goal in these upper-division courses.

Laboratory writing was a goal strongly tied to the organic course in the qualitative study. Those results were not directly borne out in the quantitative study, for which one might have hypothesized that the organic course would show a significant difference in this factor compared to all others. In the quantitative study, the analysis showed that general chemistry faculty de-emphasize this goal in comparison to faculty teaching all other laboratory courses. We believe these findings are due to the nature of the curriculum in general chemistry and provide complementary perspectives on laboratory goals. In the qualitative study, some faculty discussed the general chemistry curriculum as using fill-in-the-blank worksheets. The highly directed nature of many general chemistry laboratory programs may minimize the emphasis of writing as a goal. For example, the students may complete data collection sheets rather than using a dedicated laboratory notebook. The effect sizes indicate an increasing emphasis on laboratory writing as students move through the chemistry curriculum. Across the studies, we find evidence that laboratory writing is a goal that undergoes a step-function-like increase in emphasis from general to organic chemistry, then maintains a steady presence in the curriculum through analytical, physical, and upper-division courses.

Finally, we note in both studies that faculty described obstacles in conducting undergraduate laboratory. The expectation of offering a quality laboratory course when faced with large enrollments, a variety majors, deteriorating facilities, a static curriculum, and in some cases the management of teaching assistants is challenging. However, creatively addressing and improving this state of affairs is the responsibility of the faculty. It is with the faculty that the challenge lies, not with underprepared students, intractable colleagues, nor teaching assistants. Despite these frustrations, faculty must develop and implement laboratory curricula based on well-articulated goals.

■ IMPLICATIONS AND FUTURE RESEARCH

Reviews of laboratory and literature from across the globe call for faculty to identify their goals for laboratory rather than rely on the inherent value of laboratory as a justification for its existence.[9,11−13] The mixed-methods study described herein has identified laboratory goals held by chemistry faculty at universities and colleges across the United States and for a variety of course contexts. The identification of such goals is a necessary first step toward creating measurable goals that can be used to assess and improve the quality of university-level laboratory instruction within chemistry courses. The findings from those faculty who were interviewed and those respondents in the survey sample suggest it is imperative for all chemistry faculty at each college or university to discuss the laboratory curriculum with colleagues, both within individual courses and across the curriculum in order to articulate goals.

Perhaps more importantly, these goals must be measurable. It is critical that the outcomes of laboratory instruction provide data for improvement of the curriculum. Literature in this *Journal* describes rubrics for assessment and frameworks for iterative improvement cycles involving the development of goals, curriculum, and assessments.[30,31] It is especially important that faculty use assessments aligned with course goals that point the way toward iterative improvement of the curriculum.[30]

Whether students are aware of faculty goals for laboratory and can articulate if they have been achieved remains an open question. There is some evidence that students do not meet learning goals in laboratory of which they are unaware.[7] Researching students' perspective of the laboratory and driving forward the conversation among faculty about laboratory goals, how to develop, implement, and assess them, are the next steps in this research program.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Data analysis details of the survey: correlation tables, Cronbach's α, Kaiser−Meyer−Olkin (KMO) tests, factor analysis, and loadings. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank staff members at the Statistical Consulting Service at Purdue University for their aid with the statistical programming and consultation, as well as Steven Landry from the Department of Industrial Engineering at Purdue University and Jeffrey R. Raker of Iowa State University for their assistance in the analysis of data, especially the factor analysis. Stacey Lowery Bretz made key suggestions in the formulation of the survey and in editing the resulting manuscript. This research was funded by the National Science Foundation through grant numbers 0737784 and 0536776. 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.

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