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Faculty Perspectives of Undergraduate Chemistry Laboratory: Goals and Obstacles to Success

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> I'm glad you're doing this because, you know, how I've got myself in the habit of thinking a lot about learning outcomes in the lecture part of the course, but not always in such detail for the lab.
> —Quote from a community college faculty member who teaches organic chemistry laboratory

The body of literature addressing laboratory instruction is extensive, and recent literature reviews have discussed the significance of the laboratory and the importance of defining its' educational role *(1−3)*. Lazarowitz and Tamir wrote (*4*, p 94), "Perhaps no other area in science education has attracted so many research reviews as learning, teaching, and assessment in the laboratory".

Many faculty agree that undergraduate laboratories play a central and distinctive role in science education *(1, 3, 5−13)*. However, challenges have emerged that question the inherent merit of laboratory. For example, the goals for laboratory are often criticized as being poorly articulated or nonexistent *(2−4, 8 13, 14,)*. In the absence of clearly stated goals or learning outcomes, claims that "laboratory experiences help students understand materials, phenomena, concepts, models, and relationships" (*3*, p 46) become difficult to support. This lack of articulated goals leads to a disconnection between curricula and assessments. Further, laboratory instruction is costly; some question the logic of maintaining expensive teaching laboratories without solid evidence of its educational effectiveness *(1, 18−20)*.

Other research has decried the absence of convincing evidence regarding the educational value of laboratories *(2, 4, 8, 13, 15,−17)*. In 1982, Hofstein and Lunetta reviewed the research on laboratory work and wrote (*2*, pp 212−213):

> Researchers have not comprehensively examined the effects of laboratory instruction on student learning and growth in contrast to other modes of instruction, and there is insufficient data to confirm or reject convincingly many of the statements that have been made about the importance and the effects of laboratory teaching. The research has failed to show simplistic relationships between experiences in the laboratory and student learning.... Researchers must examine the goals of science teaching and learning with care to identify optimal activities and experiences from all modes of instruction that will best facilitate these goals.... There is a real need to pursue vigorously research on learning through laboratory activities to capitalize on the uniqueness of this mode of instruction for certain learning outcomes.

They re-visited the research-based laboratory literature in 2004 and noted that their comments of over 20 years ago remained valid *(3)*. Despite the widely held beliefs that laboratory holds a unique place in science education and that laboratory is where students interact directly with natural phenomena, Hofstein and Lunetta found "sparse data from carefully designed and conducted studies" *(3)* to support the deep-seated assumption regarding the central value of laboratory.

Despite the vast literature on laboratory instruction, many studies addressing laboratory instruction suffer methodological shortcomings such as failure to control variables, insufficient reporting of goals, curriculum, and assessments, lack of correspondence between goals and assessments, thereby generating questionable findings *(3, 20, 21)*. Thus, the call for well-designed research on undergraduate chemistry laboratory instruction persists *(1, 6, 16, 22)*.

Our goal was to execute a study that would clarify previous findings and respond to Nakhleh, Polles, and Malina's call for research on the faculty perspectives of undergraduate laboratory *(1)*. This study was designed to identify the *goals*, *strategies*, and *assessments* used by faculty members who teach, direct, or are engaged in undergraduate chemistry laboratory. Specifically, this research targeted faculty who are involved in the development and implementation of laboratory curricula at community colleges, liberal arts institutions, comprehensive universities, and research 1 institutions across general chemistry, organic chemistry, and upper-division courses at American Chemical Society (ACS)-approved institutions. In addition to investigating the type of institution and course level in the chemistry curriculum, this research explored the role of National Science Foundation Course, Curriculum, and Laboratory Improvement (NSF-CCLI) funding to improve laboratory instruction. This report focuses upon the findings regarding faculty goals.

Methods

Faculty members were chosen for interviews from two subpopulations, those who had received NSF-CCLI funding to revise the curriculum or implement innovations in the undergraduate chemistry laboratory, and those who had not. Faculty who had received NSF-CCLI[1] grants comprised one group referred to as the "successful NSF-CCLI grant writers" (SGW) group, while participants who had not received these NSF grants comprised another group referred to as the "regular faculty activity" (RFA) group. The pool of NSF-CCLI grantees was identified by searching the NSF Fastlane award search Web site *(23)* for CCLI recipients since 1995 who were at ACS-approved institutions. The RFA pool was identified through a randomized selection process to balance types of institutions from locations across

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Table 1. Sampling Matrix of SGW and RFA Faculty by Institutional Type and Course Type

Respondent Groups[b]	Community College GC	Community College OC	Community College UD	Liberal Arts GC	Liberal Arts OC	Liberal Arts UD	Comprehensive GC	Comprehensive OC	Comprehensive UD	Research 1 GC	Research 1 OC	Research 1 UD	Totals
	Number of Participants by Institution Type and Chemistry Course[a]												
SGW	0	2	N/A	1	0	2	1	1	1	2	1	0	11
RFA	0	1	N/A	1	1	1	2	0	1	2	1	1	11
Totals	0	3	N/A	2	1	3	3	1	2	4	2	1	22

[a] GC, general chemistry; OC, organic chemistry; UD, upper-division chemistry. [b] SGW, successful NSF-CCLI grant writers; RFA, regular faculty activity.

the country that were ACS approved, but had not received NSF funding.

Faculty members in both SGW and RFA groups were selected for interviews using a stratified random sample across institution type: community college (CC), liberal arts (LA), comprehensive (Comp), and research (R1). They were also stratified by course using these designations: general chemistry (GC); organic chemistry (OC); and upper division (UD). The UD classification grouped together laboratories such as quantitative analysis, physical chemistry, biochemistry, instrumental analysis, inorganic laboratory, and integrated laboratories for juniors and seniors. Community colleges are not eligible for ACS approval; thus, membership in the Two-Year College Chemistry Consortium (2YC3) was used as an alternative criterion for inclusion in the RFA pool *(24)*.

The sampling design targeted at least one faculty member of each type as indicated by the cells in Table 1. We contacted 61 faculty for interviews and 36% responded; the respondents who agreed to be involved became the participants in the study. Table 1 shows a matrix of the faculty respondents in the study and their institution type.

With approval from the Institutional Review Board at Purdue University for the project, recruitment e-mails were sent to faculty specifically identifying the laboratory course of interest for a subsequent interview. After faculty returned their signed informed consent forms, semistructured interviews were conducted via telephone, audio recorded, and transcribed. Faculty members were asked about laboratory courses taught or supervised, the goals for the laboratory, the curriculum and curricular changes, types of assessments used, and how assessment connected to the goals for the course *(25)*.

Interviews were coded using an open-coding strategy *(26)* to capture a multitude of varying responses from participants, and analysis was completed with the use of QSR Nvivo 7 *(27)*. During analysis, the constant comparison method *(26)* was employed to continuously and simultaneously compare and contrast codes that were developed from transcripts. Over 800 unique codes were developed from the open coding of 22 interviews. Codes were then successively collapsed into categories to facilitate the creation of assertions that were grounded in the data.

Transcripts for SGW and RFA groups of faculty were coded independently and subsequently compared between groups and across courses. To establish reliability, two researchers analyzed two interviews and compared their codes. The raters agreed on 247 of the 312 codes, for an inter-rater reliability of 79%. As analysis progressed into assertions, the research team also discussed the coding, categories, emergent themes, and the assertions to ensure reliability.

Findings and Assertions

Faculty Goals for Undergraduate Chemistry Laboratory

The analysis below compares faculty goals in general chemistry, organic chemistry, and upper-division laboratories. All faculty members are from ACS-approved institutions, except those at community colleges. SGW (successful NSF-CCLI grant writers) refers to faculty who received NSF-CCLI funding to implement changes in the laboratory, while RFA (regular faculty activity) refers to those who did not receive NSF-CCLI funding.

General Chemistry

Five categories emerged from the analysis of the faculty interviews that support three assertions about laboratory goals in general chemistry.

- *Assertion 1.1: SGW and RFA general chemistry faculty stated that engaging in science and mastering laboratory techniques and skills are important goals for laboratory.*

Both SGW and RFA faculty discussed the importance of helping general chemistry students learn how science works and engaging students in doing science. Consider these statements made by faculty.

> Well, I'm idealistic. I think they ought to take away the idea that somehow, this is how a, how science works.... I'd like to teach them that science is really about perseverance. You've got to keep at it. Don't get mad at yourself because you don't get the idea or the correct result immediately. This is not how science works. People work for years in trying to understand one of these things. (GC RFA respondent 5)
> To excite student interest in, and enthusiasm for, the process of scientific investigation. (GC SGW respondent 2)

These exemplars emphasize tenacity and the realization that scientists often work “without knowing what the answer” actually is. These faculty were comfortable with developing an appreciation for the investigative process in students and reinforcing the notion that questions (or testable hypotheses) drive experiments.

Both groups of faculty discussed the importance of developing laboratory skills, and learning techniques. This finding is consistent with reports present in the laboratory literature pertaining to the mastery of laboratory skills and techniques *(28)*. However, a difference emerged in the way each group discussed techniques and skills. RFA respondents articulated a more detailed perspective of techniques, frequently identifying a list of specific instruments and techniques:

> Um, learning outcomes—I'd say it's, it's rather technique-driven, so, you know, we would want them to, say, learn how

> to use a buret and titrate. We'd want them to use a spectrophotometer, a spec-20. (GC RFA respondent 1)

By contrast, SGW respondents discussed techniques and skills in a more expansive manner by describing the importance of using laboratory skills to support "broader learning goals" (GC SGW respondent 4), such as transfer to other courses:

> We also want to introduce the skills that they would need that pertain to chemistry, but really that they could carry through into their engineering courses. (GC SGW respondent 1)

and connections to chemistry content:

> To teach safety in handling and disposing of chemicals, to gain familiarity with apparatus and techniques associated with the experimental parts of chemical concepts. (GC SGW respondent 2)

Thus, although both groups of faculty discussed the importance of learning laboratory techniques and skills, they articulated differing perspectives associated with learning laboratory techniques and skills.

- *Assertion 1.2: Successful NSF-CCLI grant writers place a greater emphasis on connecting general chemistry lecture to laboratory content and on the development of critical thinking skills.*

Each general chemistry SGW respondent discussed connecting the content of lecture and laboratory. SGW faculty wanted students to "understand the chemistry at a deeper level" (GC SGW respondent 3) and "to make the content relevant" (GC SGW respondent 1). One faculty member, GC SGW respondent 2, simply stated, "To have students understand the explicit connection between lecture and lab".

We found that all general chemistry SGW faculty discussed reinforcing lecture through connecting lecture and laboratory content to promote a more integrated experience. Few of the RFA faculty discussed connections between laboratory and lecture.

SGW faculty discussed a variety of approaches to support the development of critical thinking skills. They described multiweek investigations, and the value for students of constructing and revising models based on their analysis and interpretation of experimental results. These faculty discussed critical thinking skills in ways that revealed the importance of making evidence-based decisions about experimental procedures and outcomes, such as GC SGW respondent 2:

> By developing skills in the design of experimental procedures and to learn how to use the results of one experimental plan to plan further work.

By contrast, a minority of the RFA respondents discussed critical thinking skills in the context of decision making in laboratory:

> I don't want to have uh, uh, students where we just hold them by their hand and guide them through. Do this. Do that. What we're looking for is uh, when the students come out of this, they uh, have the ability to, to judge, assess, a certain situation, and find solutions to a problem, giving uh, a framework, a basic outline, and then, they fill it in themselves. (GC RFA respondent 2)

The quotations above indicate that SGW and RFA general chemistry faculty respondents held starkly differing views of the laboratory as a medium for teaching critical thinking skills.

- *Assertion 1.3: RFA faculty place a greater emphasis on collaborative group work than SGW.*

RFA faculty had a variety of reasons for emphasizing the development of teamwork skills through collaborative learning. One faculty member, GC RFA respondent 3, linked the collaborative setting to "real-life living [and] working circumstances". Others linked it to problem solving, and discussion of data:

> One thing we do is we try to do group work so that, when students can't figure something out, they don't necessarily come to us, that they work with their partner, to, you know, discuss how this should be done, and whether the data looks right, and that sort of thing. (GC RFA respondent 1)

Only one SGW respondent discussed collaborative settings and teamwork, doing so in the context of discussing the real world:

> Some of the minor goals are that I do want the students to have to work together, uh, in, in groups, uh, and learn to, start to learn how to interact with other people. (GC SGW respondent 4)

As with Assertion 1.2, general chemistry SGW and RFA faculty respondents viewed the laboratory differently with regard to teaching teamwork and collaboration.

Organic Chemistry

In contrast to general chemistry, the organic chemistry SGW and RFA respondents described remarkably similar goals for the undergraduate laboratory. The analysis yielded three categories, each of which support one assertion.

- *Assertion 2.1: Techniques and laboratory skills, critical thinking skills, and written communication skills are similar goals for SGW and RFA faculty in organic chemistry laboratory.*

Every faculty member we interviewed who taught or had responsibility for an organic chemistry laboratory discussed the importance of learning laboratory techniques. Some provided detailed responses:

> Determine and use calibration standards, such as for a melting point thermometer.... Purify and separate products that are prepared in the laboratory by distillation, extraction, or recrystallization...to determine the identity of unknown compounds from each organic functional group using chemical and physical spectroscopic methods.... Operate a gas chromatograph and...refractometer and infrared spectrophotometer, melting point apparatus, and a visible light spectrophotometer. (OC RFA respondent 2)

Other participants offered more general remarks about laboratory techniques:

> [F]amiliarity with laboratory techniques...common techniques. (OC SGW respondent 2)
>
> Application of organic techniques to the lab and quantification. (OC SGW respondent 1)
>
> To learn essential lab skills to help them in additional courses. (OC RFA respondent 1)

Organic chemistry laboratory typically uses specific instrumentation and techniques, and thus, it was not surprising that all organic chemistry respondents discussed technique as a goal for laboratory instruction.

Two faculty members pointed out the importance of spectroscopy in identifying compounds. Consider this representative exemplar from OC SGW respondent 4:

> It continues with ah, ah spectroscopy, characterization of compounds, and then, by various means, and uh, those get more complicated as the semester progresses.

Unlike the general chemistry faculty, where critical thinking skills and scientific reasoning were points of difference between the SGW and RFA groups, the development of critical thinking skills was a common goal among faculty in the organic chemistry laboratory. OC RFA respondent 3 provided detailed arguments regarding the significance of developing students' critical thinking and scientific reasoning skills:

> Another for me is, is, really to get them to think about the material. Um, and, and that's what we talked about previously, is the major reason why we've tried to redesign or, or develop new experiments to really force students to think. Um, so that it's not just, it's not cooking class.... That's my fear of organic lab, is too often, it's a cooking class and if you end up with white solid at the end, you've been successful. And, and I don't think the students get much out of that. Um, the, the, goals about, about critical thinking—I mean, I teach, I try to teach the lab like I would uh, a recitation, or a, a group meeting, where, I, I'm just trying to ask a lot of questions, and get them to, to think about the important parts of the experiment at hand. Uh, you know, "Why did you, why did you get this result? Is this consistent with what you predicted beforehand?" So, really to, to ask them a lot of thought provoking questions, and if they don't know the answer right way, to just let them think about it, um, and, and also to try and encourage them to talk to other students in the lab, um, and not rely on the TA or the instructor for the source of answers.

Other organic faculty contrasted verification laboratories with inquiry-oriented laboratories as a way to promote critical thinking and scientific reasoning:

> To encourage critical thinking skills by doing the guided inquiry way versus the verification way. (OC RFA respondent 1)

Finally, OC SGW respondent 2 provided another perspective on the desire to develop critical thinking skills and scientific reasoning skills:

> To be able to, to apply scientific reasoning, so, because, in the laboratory, it's, it's, um, an important place where they take measurements and then draw appropriate conclusions.... That's a really important part of what makes the laboratory curriculum, I guess, in a way, distinct from what happens in lecture. Not that we aren't problem solving in lecture, but, it's different. (OC SGW respondent 2)

The majority of organic chemistry faculty in the study discussed critical thinking and scientific reasoning skills as a goal for their laboratory course. In many cases, their remarks revealed the commitment faculty have to fostering these skills in students.

All of the organic chemistry faculty who discussed written communication skills mentioned the importance of keeping a laboratory notebook:

> To have them become proficient in record-keeping, by keeping their um, notebook, as well as proficient writers, because they, beyond the notebook, they have to, um, write lab reports as well, in a journal-type format. (OC RFA respondent 1)

In addition to appropriate record keeping in laboratory notebooks, organic faculty wanted students to present their data in a formal laboratory report. One faculty member even contrasted the expectations for written communication skills in organic chemistry as opposed to those in general chemistry:

> I feel like it's a, its, it may be their only chance to do that. Um, because the general chem that is taught at our university is all fill in the blank. Very short. ... Organic is a full report.... I see organic as filling the, the niche of teaching people how to write a real lab report. (OC SGW respondent 2)

Both groups described the organic laboratory curriculum as being a primary arena for teaching scientific writing so as to aid students in future science courses.

Upper-Division Laboratory Courses

Three categories of goals emerged from the analysis of upper-division faculty interviews, contributing to one assertion. It is notable that, in contrast to organic chemistry where broad agreement in goals emerged, upper-division faculty articulated marked differences between SGW and RFA.

As described earlier, the upper-division designation groups together both junior- and senior-level laboratories. In this study, the SGW respondents were teaching physical chemistry laboratory and quantitative analysis and the RFA respondents were teaching biochemistry, inorganic, and instrumental analysis laboratory courses.

- *Assertion 3.1: RFA faculty emphasize specific laboratory techniques and skills while SGW emphasize experimental design and understanding uncertainty in measurement.*

Upper-division respondents, in contrast to the general chemistry and organic chemistry respondents in this study, do not share common laboratory goals.

Learning and mastering advanced laboratory techniques was a goal expressed by all of the RFA respondents. In discussing techniques, this group mentioned specific instruments used to physically characterize molecules:

> Advanced laboratory techniques, uh, particularly under inert atmospheres, uh, use of cyclic voltametry, uh characterization of products with infrared spectroscopy, and NMR spectroscopy, uh, use of a magnetic susceptibility, uh, balance. (UD chemistry RFA respondent 3, inorganic synthesis)

or the goal was expressed in terms of using instruments or mastering methods:

> Um, for the students to understand and be able to use analytical instrumentation, I guess. (UD chemistry RFA respondent 1, instrumental analysis)
>
> One, to uh, teach them some methods in biochemistry and cell biology, ones that they would use in a research laboratory. (UD chemistry RFA respondent 2, biochemistry)

In stark contrast, none of the SGW respondents mentioned a specific list of instruments or techniques to be mastered. All upper-division laboratory courses require the use of instrumentation to gather data; however, there was a clear difference in how the faculty who had received NSF-CCLI funding conceived of their laboratories, versus those who had not.

All of the SGW, but just one of three RFA respondents discussed aspects of experimental design in terms of designing experiments and carrying out procedures. In the quantitative analysis laboratory, UD chemistry SGW respondent 3 expected students to develop a proposal with detailed protocols:

> They have to submit to me a proposal on how they're going to get this measurement. How they're going to collect samples, and how many samples. How they're going to work them up. Uh, what instrumental parameters that they're going to use, and its all got to be grounded on, they've gone to the literature.

In physical chemistry laboratory, UD chemistry SGW respondent 2 discussed the importance of developing of a sense of accuracy in experimental procedures in terms of "sloppiness":

> [W]here you could be sloppy in the lab and where you can't.... [Consider a] crystal violet kinetics lab, because it's a pseudo-first order thing, and its run with OH in high concentration. ...[I]t doesn't matter what the concentration of crystal violet is, so long as you can see it in absorbance in the, on the spectrophotometer. It's listed at 30 ppm, but it doesn't matter if its 25 or 40, that's a place where you could be sloppy, and I'm not sure that students always recognize where you can be sloppy and where you can't. ...[S]tudents seem to try and, sort of, follow the directions too precisely sometimes.

A laboratory goal for this physical chemist was for students to develop a sense of when they needed to demonstrate fidelity to procedures, and when they could venture from the proscribed path. Across the SGW faculty there was a desire for students to engage in experimental design, to develop procedures based upon the literature and sound decision making, and to develop a more nuanced approach to laboratory practices.

All of the SGW faculty discussed uncertainty in measurements and calculated values. Those who taught physical chemistry discussed propagation of error calculations. In the undergraduate chemistry curriculum, physical chemistry is frequently the course where the mathematical basis for propagation of error calculations is addressed. Thus, it is not surprising that the physical chemists discussed this particular goal.

However, UD chemistry SGW respondent 3, who taught instrumental analysis, illustrated the goal of having students understand the uncertainty of calculated concentrations based upon experimental data:

> They've got to, uh, you know, interpret the data.... What they [the students] want to do, they've (referring to the experiments) been done before, so they can find literature values for the caffeine in chocolate, or when they see there's a lot of variability, in also nitrate or nitrite in hot dogs. So, they can find these numbers and they have to compare their numbers to the kinds of things they're finding in the literature to then say `Ok, I'm in the right ball park', and that provides some degree of confidence, that what we measured is, is a pretty good number, and, you know, the sense of at the, at the end of this, that they have a good number from the measurements that they've done. How confident do they feel in that, uh, is a key part of it....

Beyond learning how to perform a propagation of error calculation, there exists the notion that students should develop methods by which they can determine the quality of the values they measure and calculate. Thus, at the upper-division level, SGW faculty focused on developing these skills to achieve this goal.

Analysis of Problems and Limitations

During the open coding of whole interview transcripts, a code titled "problems and limitations" was developed because many faculty described obstacles and barriers to laboratory success. Not every participant described such problems in his or her interview because they were not explicitly asked to do so in the interview protocol. However, the research team became interested in the underlying features of this code and analyzed the responses. Of the 22 participants total, 13 (8 SGW, 5 RFA) are represented in this analysis of the "problems and limitations" code. The distribution of participants in the subpopulation is provided in Table 2.

Table 2. Subpopulation of Participants Included in the "Problems and Limitations" Code

Participant[a]	Institution Type[b]	Course
GC SGW #1	Comp	General chemistry
GC SGW #2	R1	General chemistry
GC SGW #3	R1	General chemistry
GC RFA #1	LA	General chemistry
GC RFA #3	R1	General chemistry
GC RFA #5	Comp	General chemistry
OC SGW #2	Comp	Organic chemistry
OC SGW #4	R1	Organic chemistry
OC SGW #3	CC	Organic chemistry
OC RFA #1	R1	Organic chemistry
OC RFA #3	LA	Organic chemistry
UD SGW #1	LA	Physical chemistry
UD SGW #2	Comp	Physical chemistry

[a] SGW, successful NSF-CCLI grant writers; RFA, regular faculty activity. [b] Comp, comprehensive institution; LA, liberal arts institution; R1, research 1 institution.

- *Assertion 4.1: Student preparation for laboratory is a concern of faculty at research 1, comprehensive, and liberal arts institutions.*

Student preparation for laboratory courses was a concern expressed by faculty across the curriculum, at every institutional type except community colleges. Many faculty described how student preparation limits and impacts student success:

> Most of them say, "Oh, yeah, you know, I've used Excel" or, "I've used this", or, "I've used that". Well, they have not used it for the purposes that we're trying to use them for.... The biggest problem we find with all students is the lack of comprehension that mathematical formulas and graphs actually represent real, physical phenomena, and it is really difficult to get them to believe that. So, we spend most of the quarter doing some sort of graphing or some sort of equation interpretation because they just cannot get it. (GC SGW respondent 1, Comp institution)
>
> We'll spend a lot of time on error analysis, which is a shame.... My one concern is that, that they're not always, that they're still somewhat immature in their ability to think things through. Uh, and so, that's something that I'm constantly harping on. (UD chemistry SGW respondent 1, LA institution)

While these data do not indicate the reason for students' lack of preparation for laboratory participation, they do suggest that changes should be implemented to better prepare students for laboratory work. Guidance for preparing students to effectively participate in laboratory and moving laboratory toward a more student-centered curriculum is available in the literature *(29)*.

- *Assertion 4.2: The ability of teaching assistants (TAs) to facilitate learning in laboratory and assess student work generates unease in faculty at institutions that use TAs.*

Concerns emerged from faculty at comprehensive and research 1 institutions related to the ability of TAs to facilitate student learning and to assess student work:

> I think it's different if I have a TA teaching versus me teaching is...this is where the TA teaching it, I'm not convinced, works as well as if I'm teaching it, because if I teach it, I can make sure that those questions get asked in the middle of the lab that I'd like them to be asking, and that students are thinking about those things.... And I'm not sure that happens if I have a teaching assistant running the lab for me. (UD chemistry SGW respondent 2, Comp institution)
>
> The report writing I think is really important, but since we rely on TAs to teach a lot of the courses, I don't feel like they [the students] come out with as good report writing skills as I would hope because the TAs don't grade them very carefully, or they [the TAs] don't know what to look for.... Now, I know there are people who are just going to say, `Take a 10 out of the air and stick it on the paper", and that's a problem, but, um, we kind of leave it up to the individual to decide exactly how to grade each one. (OC SGW respondent 2, Comp institution)
>
> This is a struggle for me to help the TAs and help the students learn that we're not just going to tell them what the answers are. ... We're going to say, "Well, what do you think? What does your data look like?" (GC RFA respondent 3, R1 institution)

The ability of TAs to successfully facilitate laboratory investigations and evaluate student work was a limitation. Faculty perceived themselves as more aware of the learning goals of the laboratory, and therefore, better able to meet those goals. These faculty are intuitively aware of the intersection between their chemistry content knowledge and pedagogy, an area Shulman defined in 1986 as pedagogical content knowledge, or PCK *(30)*. Faculty use their PCK to help students formulate concepts, address misconceptions, and connect laboratory learning to prior chemistry knowledge. The data above indicate that faculty recognized that TAs possess fundamentally different PCK and question their ability to facilitate learning. Further, when student work is assessed, faculty utilized a rubric or grading key that has been developed over time, which may also have implicit criteria. As noted by OC SGW respondent 2, in some cases, each TA is allowed to develop a grading scheme that may not be consistent with other TAs, nor be aligned with the goals of the laboratory. The majority of participants from comprehensive and research 1 institutions raised concerns regarding the skillfulness and judgment of TAs in facilitating student learning and assessing student work.

- *Assertion 4.3: Faculty involvement and accountability with laboratory development and implementation is a concern for SGW faculty at comprehensive and research 1 institutions.*

SGW faculty at both comprehensive and research 1 institutions described faculty colleagues' accountability and involvement with the laboratory curriculum as limitations. The exemplars below reveal issues related to faculty members' expectations, priorities, and workload.

> The number of faculty, real faculty, involved in anything having to do with the labs has basically gone down to zero. And, uh, my greatest disappointment as a chemist has been that the people who actually make a living as synthetic chemists, they are the least interested in the labs. (OC SGW respondent 4, R1 institution)
>
> It's been very hard to pin people down to talking about assessment instruments and actually devising assessments. Um, and that has been a real impediment, and we've had to wait for people to retire finally, because it, well, I mean. It was the junior faculty who wanted it, and it was the senior faculty who were being resistant. (GC SGW respondent 1, Comp institution)
>
> If you have a professor, you know, tenure, tenure-track person doing the grading, I mean, they're resentful because they have to spend so much time.... [...] The quizzes are very easy to grade, so that's always unambiguous, but I guess, it's such a time sink that it's really hard to demand anything else of the instructors. (OC SGW respondent 2, Comp institution)

We hypothesize that these NSF-CCLI grant recipients recognize that faculty input is required to improve laboratory curricula. The development of aligned goals, curricula, and assessments requires intellectual effort. The implementation of curricula and assessments with fidelity to course goals demands vigilance. All three of these exemplars point toward dissatisfaction with faculty involvement in laboratory curricula.

Discussion of Findings

Comparison of Goals for SGW and RFA Respondents by Course

We have chosen to illustrate the goals of the successful NSF-CCLI grant writers (SGW) and regular faculty activity (RFA) respondents with Venn diagrams to highlight the similarities and differences between groups. In each level of course—general, organic, and upper division—the SGW faculty goals are shown inside one circle, and the RFA faculty goals inside another circle. The overlap region identifies common goals between the groups and the degree to which the regions overlap is related to the general agreement among faculty pertaining to goals in that course or set of courses.

In general chemistry, both SGW and RFA faculty shared the goal of helping students to learn laboratory techniques and emphasized engaging students in the scientific process. These shared goals constitute the center of Figure 1. However, SGW and RFA faculty are also identified by goals that are not represented in the overlap regions of Figure 1. Respondents from the SGW group placed a greater emphasis on connecting lecture with laboratory and on the development of critical thinking skills as part of the investigative process. We hypothesize that the significance of these cognitively oriented goals may have originated from the consideration of revising the laboratory curriculum or implementing innovations; this hypothesis is supported by the fact that SGW faculty successively sought and secured external funding to make changes in their laboratory. In general, the RFA respondents placed greater emphasis on developing teamwork skills that would be valuable in the "real-world" of work.

Faculty in organic chemistry demonstrated a greater degree of congruity between their goals as shown in Figure 2. There was a high degree of coherence between SGW and RFA faculty on laboratory techniques and skills, critical thinking skills, and

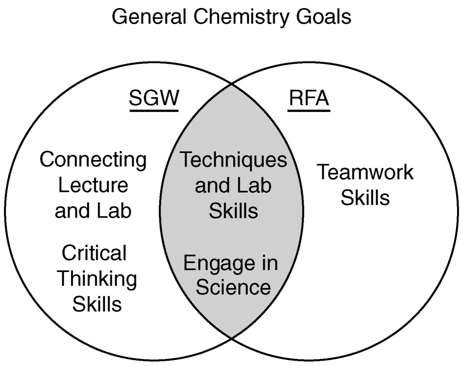

Figure 1. General chemistry laboratory goals for respondents in both groups: successful NSF-CCLI grant writers (SGW), and regular faculty activity (RFA).

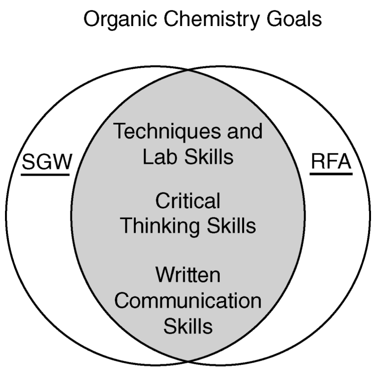

Figure 2. Organic chemistry laboratory goals for respondents in both groups: successful NSF-CCLI grant writers (SGW), and regular faculty activity (RFA).

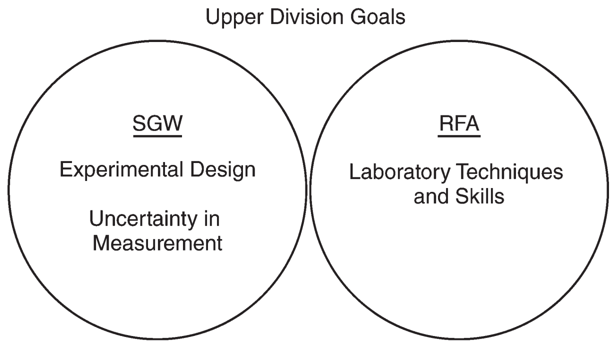

Figure 3. Upper-division laboratory goals for respondents in both groups: successful NSF-CCLI grant writers (SGW), and regular faculty activity (RFA).

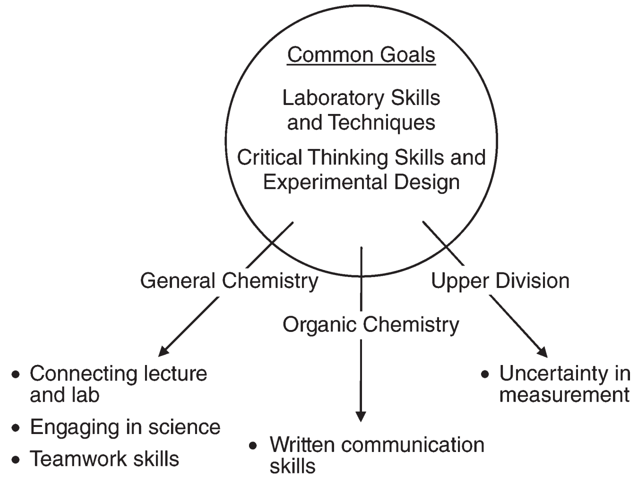

Figure 4. Laboratory goals across the undergraduate chemistry curriculum.

teamwork skills. Seemingly, the acquisition of a NSF-CCLI grant reveals little differentiation with regard to the goals of these groups of faculty.

In upper-division courses, the presence of CCLI funding generated the greatest differences with no overlap between the groups, as shown in Figure 3.

Although the faculty taught a variety of courses, RFA respondents emphasized mastering specific laboratory techniques oriented toward instrumentation and physical characterization, while SGW emphasized broader goals, experimental design, and understanding the uncertainty in measurement.

The lack of overlap between these groups is striking. The variety of courses in this upper-division group of faculty may play a role and cannot be disregarded. However, we believe it does not entirely account for the differences that emerged. As we hypothesized with the general chemistry SGW, the emphasis on cognitively oriented goals could originate from the desire to revise the laboratory curriculum and implement innovations. Further work will need to be carried out with faculty to learn more about differences this qualitative study has uncovered.

Goals for the Undergraduate Chemistry Laboratory Curriculum

What then are the similarities and differences in goals across the chemistry undergraduate curriculum? Figure 4 displays the goals held in common regardless of group membership. From this study, two common goals emerged across the curriculum. Faculty emphasize the mastery of laboratory techniques and skills, and the development of critical thinking skills and experimental design skills.

Figure 4 highlights laboratory techniques and skills as significant goals across the curriculum, even though faculty discussed these goals differently. SGW in general chemistry viewed the utility of learning laboratory techniques more broadly than did their RFA colleagues, but in organic chemistry, faculty often had specific lists of techniques that would aid in the purification and or physical characterization of compounds. In upper-division courses, RFA respondents emphasized specific techniques indigenous to their courses.

In all courses, we found instances of faculty with specific lists of instruments and techniques, while others discussed laboratory techniques in a much broader sense. It is clear that the goal of “learning laboratory techniques” carries varied and subtly different meanings across courses and among faculty. Our findings suggest that faculty need to engage in discussion within departments across courses in order to build consensus and specificity in what they mean by the phrase learning “laboratory techniques.” Further, as an outgrowth of these discussions, faculty should identify specific, measurable outcomes that would occur if students met the goal of learning these techniques.

General chemistry SGW respondents and both groups of organic chemistry respondents emphasized critical thinking skills. The focal point of this goal is the development and refinement of these skills in a laboratory environment. The ability to use an evidence-based approach in discussing data, analysis, and results is a crucial scientific skill.

Strongly associated with critical thinking skills are the aspects of experimental design discussed by the upper-division faculty. Determining experimental procedures and protocols and developing a nuanced approach to laboratory practices are related to the ways in which general chemistry and organic chemistry faculty discussed collecting and analyzing data.

Goals such as connecting lecture to laboratory, engaging students in doing science, teamwork skills, written communication skills, and uncertainty in measurement were not universally cited across the curriculum. For example, working collaboratively was an important goal for general chemistry RFA faculty, but it was scarcely mentioned by any of the organic chemistry faculty and none of the upper-division faculty. Conversely, in organic chemistry, written communication was a significant goal for all participants, but it was not an area of emphasis for general chemistry respondents or upper-division respondents. Upper-division respondents discussed uncertainty in measurement mentioning goals perhaps tied to specific courses, but general chemistry and organic respondents scarcely mentioned uncertainty.

Problems and Limitations

The characteristic that unites the "problems and limitations" assertions is faculty involvement in enhancing the quality of the laboratory curriculum. Faculty craft the learning goals for laboratory, faculty determine the curriculum appropriate to those goals, faculty design assessments, and faculty reflect upon student outcomes. If faculty members are not engaged, then the quality of the curriculum suffers, TA training is limited, and students may exhibit a "lack of preparedness." Resources are available that evaluate the roles of TAs, provide training advice, and articulate what TAs consider effective teaching strategies *(16, 31−34)*. Faculty may adapt and implement recommendations from this literature to explicitly convey expectations to TAs, engage them in periodic training activities to improve their skills, and provide effective supervision of TAs that may foster a more productive teaching environment in laboratory *(35)*.

Future Work

The results of this research will be used to design a complementary quantitative investigation in an overall sequential exploratory design *(36)*. The strength of such a design results from grounding the quantitative parameters in the findings of the qualitative analysis. The findings from this mixed methods design will facilitate triangulation.

Currently, we are piloting a survey to measure faculty choices in the design of undergraduate laboratory courses across the dimensions described in this paper. This quantitative study requires a much larger sample of faculty and will therefore enhance the generalizability of the results. We anticipate that the findings from the survey will facilitate conversations within departments about undergraduate laboratory goals and curricula.

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Note

1. The NSF-Course Curriculum and Laboratory Improvement (CCLI) program has been changed to Transforming Undergraduate Education in Science, Technology, Engineering, and Mathematics (TUES). See http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5741 (accessed Sep 2010).

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