JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

What Faculty Interviews Reveal about Meaningful Learning in the Undergraduate Chemistry Laboratory

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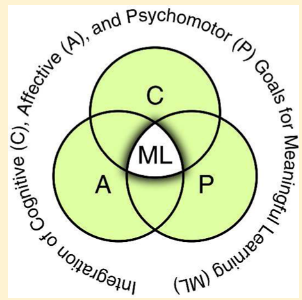
Supporting Information

ABSTRACT: Forty chemistry faculty from American Chemical Society-approved departments were interviewed to determine their goals for undergraduate chemistry laboratory. Faculty were stratified by type of institution, departmental success with regard to National Science Foundation funding for laboratory reform, and level of laboratory course. Interview transcripts that were coded and analyzed using the lens of meaningful learning reveal the importance of cognitive and psychomotor goals relative to affective learning, particularly in organic chemistry and upper-division chemistry laboratory courses. This research reveals that the undergraduate chemistry laboratory offers multiple opportunities for faculty to articulate learning goals across the cognitive, affective, and psychomotor domains. Furthermore, these goals are accessible across the undergraduate chemistry curriculum from general chemistry through organic chemistry and into a wide array of upper-division laboratories. In this study, faculty showed a decreasing emphasis on affective goals in organic chemistry and upper-division courses. Whether affective goals should be a part of the organic and upper-division chemistry curriculum remains a question for faculty to discuss.



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

FEATURE: Chemical Education Research

INTRODUCTION

In the epigraph to *Educational Psychology: A Cognitive View,* philosopher David Ausubel[1] writes (p vi):

> *The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.*

This short statement grounds all of Ausubel's work on education. The foundation of his *assimilation theory* is rooted in the idea that "reasoning capacity is primarily a function of the adequacy of the relevant conceptual framework a person has in a specific domain of knowledge".[2,3] To put it another way, a chemistry student maintains a mental structure of existing knowledge that is used to incorporate new concepts encountered in chemistry courses and, ideally, in daily life. Ausubel calls the process of making these "nonarbitrary" connections between old and new ideas *meaningful learning.*[1] As Bretz summarizes, three criteria must be met in order for meaningful learning to occur: (i) relevant prior knowledge of the student; (ii) meaningful material organized by the teacher to connect to this prior knowledge; and (iii) the conscious choice of the student to make connections between the prior knowledge and the new meaningful material.[2]

It is important to note, however, that students often become accustomed to rote learning, in which case a student merely memorizes concepts, instead of connecting them purposefully to prior knowledge. Herron[4] claims that students pursue this strategy because of their desire to put forth the "least cognitive effort". In other words, students typically do not want to expend the effort needed for meaningful learning, at least not without proper motivation.[4] Rote learning and meaningful learning are at odds with each other.

What can be done to bring students to learn chemistry in a meaningful way? Of the three meaningful learning criteria, only one lies within reach of the teacher, namely, to make the chemistry content available "in such a manner that it can be connected to students' prior knowledge and be of sufficient interest that they might choose to do so".[2] The other two meaningful learning criteria are under the control of the student. The student brings prior knowledge (or not) to the learning environment, and the student decides whether to learn meaningfully (or not). Bodner argues that "[this model] requires a subtle shift in perspective for [teachers]; a shift from someone who 'teaches' to someone who tries to facilitate learning; a shift from teaching by imposition to teaching by negotiation".[5] Knowledge cannot be passed verbally from teacher to student; therefore, students should be active participants in the learning process so they might construct knowledge within their own minds.

Published: February 8, 2013

Novak's theory of education, which he calls human constructivism, offers a powerful framework for chemistry teachers to guide students toward meaningful learning in the chemistry laboratory. Novak explains that "meaningful learning underlies the constructive integration of thinking, feeling, and acting, leading to human empowerment for commitment and responsibility".[3] Thus, in this model, faculty are compelled to provide learning experiences for their students in each of these three learning domains: cognitive, affective, and psychomotor.[2] This manuscript reports the results of a research study regarding an analysis of faculty goals for the undergraduate chemistry laboratory curriculum across the cognitive, affective, and psychomotor (CAP) learning domains.

■ AIMS AND GOALS OF LABORATORY IN CHEMISTRY

Previous reviews and studies have examined the goals for laboratory in science in a broad sense and for undergraduate chemistry.[6−9] Rather than recapitulate the information from these sources, we shall focus on their findings and perspectives on the goals of laboratory.

Hofstein and Lunetta[6,7] state that the goals for laboratory learning are nearly synonymous with "learning science more generally" (ref 7, p 38). They note that (ref 7, p 38):

> *[L]aboratory experiences have been purported to promote key science education goals including the enhancement of students':*
>
> - Understanding of scientific concepts
> - Interest and motivation
> - Scientific practical skills and problem solving abilities
> - Scientific habits of mind (more recent)
> - Understanding of the nature of science (more recent)

To guide pedagogical approaches and focus on specific targets for student learning in the laboratory, it is imperative to clearly articulate goals. These learning objectives or goals serve as the basis for curriculum development and subsequent assessment.

The role of laboratory has been discussed by numerous authors and questioned famously by Hawkes.[10] Reid and Shah[9] recently wrote (p 174):

> *However, very little justification is normally given for their [laboratories] presence today. It is assumed to be necessary and important. It is taken for granted that experimental work is a fundamental part of any science course and this is especially true for chemistry courses. Very frequently it is asserted that chemistry is a practical subject and this is assumed, somewhat naïvely, to offer adequate justification for the presence of laboratory work.*

In a review of Australian tertiary laboratory programs, Rice, Thomas, and O'Toole noted that the "aims and objectives of lab experience as a whole were tacit" (ref 11, p 40). This lack of explicitness regarding goals for the laboratory points toward the uncritical view of many faculty who simply assume a connection between laboratory activities and student learning.

Reid and Shah[9] developed a set of four holistic aims for laboratory: skills relating to learning chemistry; practical skills; scientific skills; and general skills. Other researchers have also listed laboratory aims.[9,12−19] Some of these lists have also included affective aims pertaining to student interest,[12] attitudes to science and scientific attitudes,[19] and enhancing motivation and building confidence.[20]

Bruck, Towns, and Bretz[21] recently reported faculty goals and obstacles to learning in the chemistry laboratory across general chemistry, organic chemistry, and upper-division laboratories. These goals were derived from a qualitative study carried out via interviews and analytic techniques designed to allow the goals for laboratory to emerge from the words of the faculty.

There is a need to characterize these goals across cognitive, affective, and psychomotor domains that rest upon a foundation of meaningful learning as Novak's theory describes. Without a richer understanding of the goals that faculty prioritize to shape and guide learning in the laboratory, little progress can be made toward understanding the complexities of student learning and, ultimately as Nakhleh, Polles, and Malina wrote, whether *the goals of faculty and students are in any kind of alignment*.[22]

■ GUIDING RESEARCH QUESTIONS AND METHODS

The theoretical framework that guides this inquiry asserts that, in order for meaningful learning to take place, students must experience the integration of their thinking, doing, and feeling. That is, they must learn chemistry through all three of the learning domains. Given that chemistry faculty design the learning environment of the laboratory, faculty are ultimately responsible for how students experience learning across the cognitive, affective, and psychomotor domains. This research reports the results of an investigation into faculty goals for learning in the laboratory, specifically addressing the following questions:

1. What CAP goals for undergraduate chemistry laboratory do faculty hold?
2. How are faculty CAP goals characterized across general, organic, and upper-division chemistry?

Data Collection and Analysis

To answer these questions, it was necessary to elicit the perspectives of chemistry laboratory faculty members. According to Lincoln and Guba,[23] while it can be assumed that a single construction (i.e., conceptual understanding) exists for the phenomenon that occurs upon the addition of a particular acid to a particular base, the same cannot be said when investigating social contexts (ref 23, p 230):

> *[I]t seems better to assume the existence of multiple social realities as constructed by the several participants (not to mention yet another such reality constructed by the investigator him- or herself).*

To ensure a diversity of respondents, faculty participants were sampled from two subpopulations: *innovators* (INN) were defined in this study as faculty from chemistry departments that had received a National Science Foundation (NSF) grant after 1995 from the Course, Curriculum, and Laboratory Improvement (CCLI) program to specifically improve laboratory, that is, to make changes in laboratory teaching techniques or curriculum design at their institutions. *Status quo* (SQ) faculty were sampled from departments that had not received such funding.[24] Both the innovative and status quo populations were stratified by institution type, including mission (Research 1, Comprehensive, Liberal Arts, and Community College), public or private, size (population), and by the level of chemistry laboratory the participants taught: general chemistry, GC; organic chemistry, OC; or upper division, UD. This ensured

Table 1. Sampling Matrix for Innovator and Status Quo Participants

	Number of Participants Associated with Each Institutional Type[a] and Course Type												
	CC Course Types			LA Course Types			Comp Course Types			R1 Course Types			
Faculty Participant Subpopulation	GC[b]	OC[c]	UD[d]	GC[b]	OC[c]	UD[d]	GC[b]	OC[c]	UD[d]	GC[b]	OC[c]	UD[d]	Participant Totals
Innovators	1	2	—[e]	2	1	3	2	1	1	4	0	2	19
Status Quo	1	2	—[e]	2	2	2	3	1	2	2	2	2	21
Totals	2	4	—[e]	4	3	5	5	2	3	6	2	4	40

[a]Community College (CC); Liberal Arts (LA); Comprehensive (Comp); Research (R1). [b]GC, general chemistry courses. [c]OC, organic chemistry courses. [d]UD upper-division chemistry courses. [e]This course type is usually not available at community colleges.

the full spectrum of institution types and laboratory courses was represented in the sample. Only institutions with American Chemical Society (ACS) approved four-year programs were included in the sampling. (Given that community colleges are ineligible for such approval, membership in the Two-Year College Chemistry Consortium, 2YC3, was used as an alternative criterion.) These stipulations ensured that all participants were members of a department whose undergraduate chemistry curriculum was approved by its primary professional society.

Research teams at two collaborating institutions, Miami University and Purdue University, carried out the study. We jointly developed recruitment strategies, analysis perspectives and techniques, and emergent findings by collaborating via email, holding joint project meetings with all researchers and the project evaluator, and meetings between the collaborating principal investigators and the evaluator. This method of collaboration helped to ensure the reliability and validity of the research design, data collection and analysis, emergent findings, and manuscripts developed from the project.

After obtaining the necessary IRB approvals, we contacted 112 faculty; these efforts yielded an overall response rate of 36% (approximately 50% of innovator faculty and 25% of status quo faculty responded). Table 1 shows the distribution of the 40 faculty interviewed.

Semistructured interviews were conducted with 40 college chemistry faculty members, using a common protocol (see the Supporting Information). Of these 40, 19 faculty were classified as innovators, while the remaining 21 faculty were at institutions that were considered to be maintaining the status quo based on the absence of any NSF funding for laboratory reform. Each interview was transcribed, coded, and reductively analyzed to find themes or patterns in faculty goals for laboratory.[25,26] In addition to findings from an open-coding analysis,[21] Novak's theory of human constructivism was used to address the guiding research questions reported herein. To address research question 1, faculty-identified goals were coded as cognitive, affective, or psychomotor. One set of 19 interviews obtained by the research team at Miami University were analyzed at the individual faculty level, noting the innovator or status quo classification of faculty member. To address research question 2, faculty goals were compared within each course among innovators and status quo groups using 21 interviews obtained by the research team at Purdue University. Overall, the method of analysis followed an inductive path, allowing the themes and patterns to emerge from the data. In keeping with human subjects research protocols, all names used are pseudonyms. Each quote is annotated with information identifying the participant as follows:

- Pseudonym indicating sex
- Institutional type using the codes from Table 1 (CC, LA, Comp, and R1)
- Sample codes using INN for innovator and SQ for status quo
- Course type using codes from Table 1 (GC, OC, and UD)

This convention allows the reader to identify the institution, course, and NSF funding situation for each participant in the study, and it adds further depth and detail.

■ ANALYSIS LENS 1: COGNITIVE, AFFECTIVE, AND PSYCHOMOTOR GOALS OF FACULTY

Cognitive Findings

Cognitive goals involve propositional knowledge (demonstrating factual or conceptual knowledge), procedural knowledge (demonstrating how), and strategic knowledge (demonstrating that one knows when and where to apply propositional and procedural knowledge). In our analysis of interview transcripts, six *cognitive* goals emerged.

Most faculty spoke of laboratory as important in its *relationship to content presented in lecture*. Joan talks about the importance of students making these connections:

> *Well, mostly I want it to be supportive of what we're doing in the lecture. So when we're working problems in the lecture, then they have done something similar in the laboratory, but of course messier...They've got to sift through all the information to pull out what's needed, instead of having a neat little two or three sentence like a problem is at the end of the chapter.*

[Joan, CC/SQ/GC]

Neil, a faculty innovator, discussed that the most fundamental goals for the laboratory were to not only teach physical chemistry concepts, but also to teach concepts borne from current research. He wanted lab to be connected to lecture, but also to *provide a wide range of content* by connecting current research to the "everyday lives" of the students:

> *So, one of the goals—one of them was to bring current research—is to teach the fundamentals of physical chemistry, make sure the students understand that, and complement what they get in the lecture classes. Um, that's the most fundamental—the most important. At the same time, doing that in terms of some of the experiments that have relevance to current things that the students know about in other chemistry—and outside of chemistry—topics, such as relationships to biology, medicine, things that they see in their current everyday lives.... To bring some relevance to...the experiments in addition to covering the fundamentals.*

[Neil, R1/INN/UD]

dx.doi.org/10.1021/ed300384r | J. Chem. Educ. 2013, 90, 281−288

Andrew spoke of the connection between laboratory and lecture as well, especially to *emphasize conceptual understanding*:

> *The overriding goal for most of [the laboratory environment] is a conceptual understanding. [...] Probably the major goal is then conceptual understanding of what is going on.*
>
> [Andrew, LA/INN/GC]

Faculty cognitive goals also included an emphasis on connecting the ideas learned in the chemistry lab to other sciences and mathematics:

> *[T]o integrate the disciplines....two modules focused on chemistry; two focused on biology....this was a way that the students could sort of integrate together and see the connectivity between the two disciplines.*
>
> [Chris, LA/INN/OC]

> *We're trying to figure out ways of having students realize that concepts should not be compartmentalized within a given, uh, context of a given course, that these are used all the way through their time at the college. And that's particularly true in chemistry: what you learn in g-chem you're going to revisit in organic, in p-chem, in biochem, and, and inorganic; you carry these concepts, maybe with a slight differentiation from one class to another.*
>
> [Sarah, LA/INN/GC]

The fifth theme that emerged in coding for cognitive learning goals was *critical analysis*. Consider how Clare and Joan describe the analysis that is important for their students:

> *And through the research experience we are having them involved in, we'd like to see if we can get students involved in more of the scientific process skills. So the actually thinking about how you design a scientific experiment, um, carrying out an experiment, and having the opportunity to revise it, change it, you know basically make mistakes and learn how to really make claims from the data. So to be able to look at data that is collected and determine what is a valid claim and what is not, which is pedagogically a really different exercise than "did I get the right answer when I collected this data"'?*
>
> [Clare, R1/INN/GC]

> *In other words, how to handle what they collect and what's a reasonable answer....If they're doing a molecular weight by freezing point depression...and they get a molecular weight of like 0.05, shouldn't they be a little surprised? Or if they got a negative number, shouldn't they be surprised and question what they got?*
>
> [Joan, CC/SQ/GC]

While both of these faculty expressed the importance of their students' thinking critically about their data, Claire discussed the scientific process and described the experience a student ought to have as a researcher, while Joan went into detail about the specific chemistry concepts she expected a student to be able to know. Clare was focused on the whole of the laboratory experience whereas Joan was more concerned with the finer details of each experimental procedure. Indeed, the prominent trend among cognitive goals was one by which innovators demonstrated a holistic view, while status quo professors focused on the minute details involved with the implementation of the course, such as Sean and the importance of computational software:

> *[T]hat's sort of a challenge because you've got these students coming in who really don't know much of anything about quantum...when you do...some type of semiempirical calculation.*
>
> [Sean, Comp/SQ/UD]

The sixth theme to emerge from analysis of the transcripts pertained to *communicating with the scientific community*, which we viewed as a goal involving *strategic knowledge*. Angela emphasized why she considered scientific communication skills to be very important:

> *[T]o be as specific as possible, to avoid saying things like "my numbers were off", you know what does that mean? I want them to articulate their understanding of the concepts, what they learning in the lab, using appropriate language, you know, language of the field—you know, so and being as direct as possible and as focused as possible when they're writing.*
>
> [Angela, CC/INN/GC]

John also emphasized the importance of communication skills to a wide variety of future endeavors:

> *Uh, we emphasize such things as developing writing and, uh and, uh communication skills. [...] And we make people revise their writing; it's very important to do that, or you don't learn. We also have people give oral presentations to the class on topics that are related to the lab. [...] I believe that no matter what they do, if they go on in chemistry, they will be involved in communication. And, and that their communication skills often differentiate them versus other people. So it's very important to be able to write well, and to speak well.*
>
> [John, R1/INN/UD]

The goal of developing communication skills to disseminate information was a common goal among professors, transcending the boundaries of course level and institutional type.

Affective Findings

The affective domain pertains to feelings and values including appreciation, enthusiasm, and motivation. Faculty voiced three affective goals: *making connections to the real world*, *engaging in collaboration*, and *gaining independence*. Consider this rationale offered by an innovator creating new problem-based learning laboratories which discusses goals related to the affective domain:

> *[W]e're trying to use these scenarios, the contexts, as a way of embedding learning within another context that exists in the real world.... We weren't looking to prepare anybody for a particular kind of job; we just wanted job-related scenarios to be part of what they were learning.*
>
> [Carl, R1/INN/GC]

Connecting laboratory activities to the "real world" or scenarios that might pique student interest was a pedagogical method faculty used in hopes of enhancing student learning. The analysis of interviews revealed faculty discussing all three of these goals by connecting to emotions and values via appreciation, interest, and attitude. Thus, connecting to the real world was a way to help students appreciate or value the laboratory activity differently; engaging in collaboration was a method of promoting positive feelings about the lab and other students; and gaining independence in working in the lab indicated the value of building student confidence and positive attitudes.

 dx.doi.org/10.1021/ed300384r | J. Chem. Educ. 2013, 90, 281−288

No pronounced trends emerged in this domain of learning. In fact, when the goals were analyzed, fewer faculty articulated common affective goals, in contrast to both the cognitive and psychomotor domains in which several commonalities emerged.

Psychomotor Findings

Psychomotor goals relate to physical skills such as manipulating equipment (objects) and carrying out techniques (performing a sequence or sequences of activities). Faculty emphasized *learning laboratory techniques* and *using laboratory equipment* across all institution types, funding sources, and courses as a psychomotor goal. As with goals pertaining to the cognitive domain, the innovators demonstrated a holistic point of view while the status quo participants gave very detailed explanations of student actions. For example, David had a very specific list of techniques and instruments that he wanted students to master and use:

> *It's to make sure that they're all hands-on users of all the major equipment in the department. [...] All my people who go through my advanced synthesis lab become users of the high-field NMR, users of the GC Mass Spec, any kind of equipment. [...] As much as possible, I try to introduce, you know, experiments that will use that kind of instrumentation as well.*
>
> [David, LA/SQ/UD]

By contrast, Chris, an innovator, spoke broadly about learning "appropriate techniques":

> *But probably the most importantly, there's a — third week was meant to sort of build on some of the skills they learned in the two previous weeks. So, I guess overall goals would be to um, to uh teach appropriate techniques, um also to in general learn how — or to have the students learn something about how the whole process of a synthesis works.*
>
> [Chris, LA/INN/OC]

The practical nature of the chemistry laboratory emerged repeatedly in faculty discussion of goals. However, there was a dichotomy between the holistic goals of innovators and the detail-specific goals of status quo participants.

Summary

The cognitive, affective, and psychomotor goals of faculty across all institutions and levels of course are summarized in Table 2.

Table 2. Faculty Goals Summary for Chemistry Laboratory

Learning Domain	Goals[a]
Cognitive	Conceptual understanding
	Make connections to topics in lecture
	Make connections to other fields
	Critical analysis
	Experience a range of content
	Communicating to the scientific community
Affective	Relate experience to the real world/make it relevant to future jobs or courses
	Collaboration/teamwork
	Independence in the laboratory
Psychomotor	Learning laboratory techniques
	Using laboratory equipment

[a]Goals that emerged from interviews with faculty members, $N = 40$.

ANALYSIS LENS 2: COMPARING CAP GOALS BETWEEN INNOVATORS AND STATUS QUO FACULTY WITHIN GENERAL, ORGANIC, OR UPPER-DIVISION CHEMISTRY LABORATORY COURSES

Having analyzed faculty goals for learning in the undergraduate laboratory regarding the presence and integration of cognitive, affective, and psychomotor learning goals, the data were reductively analyzed to identify any differences between innovators and status quo faculty based on the level of the chemistry course; namely, general chemistry versus organic chemistry versus upper-division laboratories.

General Chemistry

In general chemistry, analysis of the ways the groups described their goals revealed that innovators and status quo faculty valued different cognitive goals. Innovators emphasized both *connecting lecture to lab* (cognitive) and *critical thinking* (cognitive) more often than the status quo faculty. For example, innovators discussed the value of having a strong connected content base and making it relevant:

> *What I'm really looking for is uh, students to come out with a good understanding of chemistry ideas, and so, that is really what I'm focused on, particularly.... My main goal is for them to understand the chemistry at a deeper level.*
>
> [Carleigh, R1/INN/GC]
>
> *We wanted to make the content relevant to the engineers...So, um, we, this is what the whole thing has been, is trying to, um, make sure that they have good, solid content.*
>
> [Amy, Comp/INN/GC]

The innovators repeatedly discussed *critical thinking* skills such as planning future experiments and developing mental models of the microscopic and macroscopic transformations in lab. In particular, using the analysis of results to plan future work was important to Bill:

> *[B]y developing skills in the design of experimental procedures and to learn how to use the results of one experimental plan to plan further work.*
>
> [Bill, R1/INN/GC]

In addition, Carleigh (R1/INN/GC) discussed "constructing and refining models" as the goal of many of the laboratories in her course.

Both groups mentioned the importance of *appreciating how science works* as an affective goal. For example, Ray (Comp/SQ/GC) stated:

> *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, and we're giving you lots of things to understand, and it's just not going to work if you think you ought to be able to get it one thought and you can't.*

The general notion of engaging in science as a route to exciting "student interest in, and enthusiasm for, the process of [science]" as Bill stated (R1/INN/GC) was discussed by both groups as a method of developing a general appreciation for the way scientists collect data, develop hypotheses and models, test them, and use evidence to support their claims.

dx.doi.org/10.1021/ed300384r | J. Chem. Educ. 2013, 90, 281−288

However, a difference between the innovator and status quo groups emerged in the affective domain over *collaboration/group work*. Many of the status quo faculty discussed developing teamwork skills, *collaboration*, or group work as Molly and Neil did:

> *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, [but] 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.*
>
> [Molly LA/SQ/GC]

> *That begins with working, uh, in a group, working in a, in a laboratory room with many people.*
>
> [Neil R1/SQ/GC]

Only one of the innovators discussed collaboration, describing it as a minor goal:

> *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...[and] appreciate some aspects of the way in which science can occur in social contexts.*
>
> [David LA/INN/GC]

The data strongly suggest that the status quo faculty emphasized *collaboration* (affective) more than innovators in general chemistry.

Both groups of faculty emphasized the psychomotor goal of *learning laboratory techniques*. As Peter (Comp/SQ/GC) noted, "for the lab, learning outcomes would be basic lab techniques"; other status quo and innovator faculty spoke of this as well. There were comments associated with learning specific laboratory techniques such as titrations or how to use common pieces of equipment such as spectrophotometers.

Organic Chemistry

Faculty in organic chemistry demonstrated a remarkable coherence regarding goals. Both innovators and status quo faculty emphasized *critical thinking* and *scientific writing* as cognitive goals. The approach to experiments in terms of learning the scientific method or engaging in inquiry highlighted the importance of generating hypotheses, developing protocols, and analyzing and interpreting results. The quotes from Evan and Samantha below both emphasize the importance of the development of *critical thinking* skills:

> *[C]onstructing an understanding of, uh, the scientific method, and that's one of the more important outcomes...application of the scientific method to organic uh, research and experimentation.*
>
> [Evan CC/INN/OC]

> *[T]o encourage critical thinking skills by doing the guided inquiry way versus the verification way.*
>
> [Samantha R1/SQ/OC]

Many of the organic faculty discussed communicating with the scientific community through keeping "a good [laboratory] notebook" as Ginny (CC/INN/OC) remarked, or creating formal laboratory reports and oral presentations to the class.

There was strong agreement across innovator and status quo faculty regarding the importance of mastering specific types of *laboratory techniques*. Faculty repeatedly mentioned this psychomotor goal in varying degrees of detail. For example, Trent (CC/SQ/OC) gave a detailed list of the laboratory techniques that he expected students to become efficient and effective at using:

> *[D]etermine 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.... Determine identity of unknown compounds from each organic functional group using chemical and physical and spectroscopic methods...operate a gas chromatograph and infrared spectrophotometer, melting point apparatus, and a visible light spectrophotometer...use microglassware and 19/22 standard taper glassware to perform assigned experiments.*

Organic chemistry is clearly a course that is strongly guided by the goal of learning techniques, independent of whether the faculty member has received CCLI funding.

In contrast to the discussion and agreement regarding cognitive and psychomotor goals, there was a remarkable lack of discussion of affective goals across the organic faculty. Mention of affective learning was essentially absent from the organic chemistry data set and dwarfed by the importance faculty placed on cognitive and psychomotor goals.

Upper-Division Courses

This category contains faculty who teach biochemistry, instrumentation, inorganic synthesis, physical chemistry, and other integrated advanced labs. Although the specific area of chemistry varies across this group, the cognitive, affective, and psychomotor goals that function in concert with the content were analyzed.

Upper-division faculty did not agree upon goals across the innovator and status quo groups. Innovator faculty accentuated the importance of having students explore *experimental design* (cognitive) and *error analysis* (cognitive):

> *I tell them, in fact, don't go looking for a literature prep or a literature example...I want you to do this on your own and I want to know what works.*
>
> [Jason, LA/INN/UD]

> *[The experiments] have been done before, so they can find literature values for ...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, and the whole idea that creating standards and measuring the standards and, you know, comparing standards to this unknown, where there's matrix separation and so on. Um, they have to think about lots of issues, uh, as they think about their, you know, putting a final report together.*
>
> [Lonnie LA/INN/UD]

However, status quo faculty briefly mentioned these two goals, one of which is illustrated below:

> *We have the goal that they should be able to do error analysis to justify the results, the measurement is right in terms of accuracy and precision...error propagation for initial measurements, which has of course uncertainty...they have to know how. . .what's wrong with that uh data, I mean.*
>
> [Kelly, LA/SQ/UD]

The faculty also discussed psychomotor goals differently. Status quo faculty described specific methods and *laboratory* *techniques* (psychomotor) that they wanted students to master, whereas innovators intertwined remarks about *experimental design* (cognitive) with *laboratory techniques* (psychomotor), such as collecting and preparing samples, extracting an analyte from a matrix, and preparing standards. As with the organic faculty, affective goals were only briefly mentioned and were not emphasized by either group.

Analysis across Courses

Moving from general, to organic, and then upper-division chemistry laboratories, there was a marked decrease in emphasis on affective goals. Perhaps it reflected the faculty notion that they did not need to maintain student interest in chemistry. If students were enrolled in an upper-division laboratory course, they were likely expected by faculty to have shown a de facto interest by majoring in chemistry. However, student expectations do not mitigate the desirability of explicitly connecting all three learning domains in order to promote meaningful learning.

Innovator faculty in general chemistry demonstrated the greatest degree of interconnectivity among cognitive, affective, and psychomotor goals by their presence and connectedness in describing all three types of goals. As the analysis progressed through the undergraduate curriculum from organic chemistry to upper-division courses, there was decreased evidence in support of connectivity across goals. Organic faculty demonstrated a high degree of association between cognitive and psychomotor goals, but voiced scant support of affective goals. Upper-division innovator faculty intertwined and connected cognitive and psychomotor goals, while status quo faculty did not. Neither group emphasized affective goals.

■ CONNECTIONS TO NSF-CCLI FUNDING

Through both analysis lens 1 and analysis lens 2, innovator faculty repeatedly emphasized goals that were "big picture", such as connections to other courses and developing critical data analysis skills for research. By contrast, status quo faculty were very specific in articulating appropriate techniques and procedures that students were to learn in each laboratory. Recalling that innovator faculty had received NSF-CCLI funding to improve laboratory, it is interesting to note that general chemistry faculty voiced goals across all three domains. Perhaps the quest for CCLI funding and the subsequent receipt of the grant energized faculty to consider affective goals in a way that organic faculty and upper-division faculty did not. The organic laboratory curriculum is seemingly impervious to impacts on goals and connectivity through CCLI funding. The coherence of cognitive and psychomotor goals between the two groups of organic faculty was striking. Among upper-division innovator faculty, but not status quo faculty, cognitive goals were emphasized as related to experimental design and error analysis. It is possible that innovator faculty were prompted to carefully consider these goals during proposal preparation and after receiving funding.

We note that the design of the study aimed for a diversity of respondents and sought faculty who desired to make changes in their laboratory teaching techniques or curriculum design at their institutions. Thus, the study used a purposeful sampling of two groups of faculty, those who had received NSF-CCLI funding to support improvements in the undergraduate laboratory and those who had not received NSF-CCLI support. It is a limitation of this study that internal funding support for laboratory was not explicitly investigated. We note that faculty might have made changes to their laboratories in the absence of support from the NSF-CCLI program via internal funding mechanisms and it is equally likely that these faculty would have been in the innovator or status quo groups. Thus, any influence due to such internal funding mechanisms is present in both groups of faculty.

■ IMPLICATIONS FOR UNDERGRADUATE LABORATORY

The study and findings from this research are predicated upon the assumption that the clear articulation of faculty goals for undergraduate chemistry laboratory is an important and necessary activity for achieving meaningful learning in the laboratory. We used Novak's theory of education as a framework for investigating laboratory goals. An implication of this study is that faculty can classify their goals for laboratory as cognitive, affective, and psychomotor within a course and across the entire undergraduate curriculum. This can be a springboard for discussion among faculty as to the appropriateness of goals in specific courses and overarching goals across the curriculum.

For example, there is great agreement across the data set that learning laboratory techniques and using equipment are important goals in every chemistry laboratory course. While some faculty listed specific techniques for students to master, others voiced a more applications-oriented approach that required students to demonstrate an understanding of which analytical or synthetic technique would be appropriate to answer a specific question or achieve a specific goal. Thus, faculty colleagues should discuss whether the goal is to simply expose students to a technique so that some form of mastery is achieved, or whether the emphasis should be on understanding when a technique is appropriate to use. Perhaps faculty would prioritize a list of techniques and determine that exposure was acceptable in some cases while greater applied understanding was most beneficial in others.

We found a decreasing emphasis in affective goals across the curriculum. These goals relate to feelings and values—appreciation, motivation, and attitudes. While these descriptions of goals may seem foreign to some faculty, Novak's theory of learning recognizes the importance of the student's conscious choice to learning meaningfully, which is related to affect. We found that faculty enacted these goals by means of using relevance: specifically relating the chemistry material under study to areas of student interest. Agricultural majors and future nurses in our general chemistry and organic chemistry classes likely do not have the same attitudes, interests, and motivations as chemistry majors. Thus, linking chemistry content and curricula to real-world scenarios that are associated with areas of science that the students appreciate and value is a way to implement affective goals. This includes connecting relevant content from other mathematics and science courses.

Finally, as a further question to ponder concerning goals for undergraduate chemistry laboratory, we would recommend that faculty consider what evidence they would accept as students meeting each of their goals. Goals, assessment, and curricula are tied together as a functioning unit in the classroom. Goals that have no assessment component are ineffective because faculty cannot use them to determine the efficacy of the laboratory program: they cannot determine the impact on student learning nor justify the existence of laboratory activities.

CONCLUSIONS

The findings of this research reveal that cognitive, affective, and psychomotor goals are discernible across the undergraduate chemistry curriculum from general chemistry through organic chemistry and into a wide array of upper-division laboratories. Our analysis demonstrates that cognitive, affective, and psychomotor goals are present in general chemistry, but the presence of affective goals subsequently fades away by the third and fourth year. Whether faculty believe that such affective goals should be a part of the organic and upper-division curriculum is an open question.

However, Reid and Shah have noted that aims related to cognitive and psychomotor goals "*are a part of giving the student an appreciation of the way chemistry, as a science, works*".[9] It is possible that organic and upper-division chemistry faculty tacitly assume that enrolling in such laboratory courses is a proxy for student attitudes and motivation that are in alignment with their own; thus, they do not explicitly formulate affective goals. However, the presence or absence of affective goals in laboratory courses across the curriculum is deserving of further investigation.

To guide students toward meaningful learning, Novak's theory of education offers a powerful framework for the discussion of laboratory goals. When faculty and departments undertake the work of revising courses and curriculum, and in doing so, debate the purposes of and goals for their students' laboratory work, the CAP framework offers a concrete method for faculty to assess the alignment of their goals with one another and with their courses.

ASSOCIATED CONTENT

Supporting Information

The interview protocol for the study. 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

The authors wish to thank Renée Cole for her engagement as the evaluator on this project. We are also very grateful to the faculty who participated in our interviews. This research was supported by the National Science Foundation under Grants No. 0737784 (CCLI) and No. 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.

REFERENCES

(1) Ausubel, D. P. *Educational Psychology: A Cognitive View*; Holt, Rinehart, and Winston: New York, 1968.
(2) Bretz, S. L. *J. Chem. Educ.* **2001**, *78* (8), 1107−1110.
(3) Novak, J. D. *A Theory of Education*; Cornell University: Ithaca, NY, 1977.
(4) Herron, J. D. *The Chemistry Classroom: Formulas for Successful Teaching*; American Chemical Society: Washington, DC, 1996.
(5) Bodner, G. M. *J. Chem. Educ.* **1986**, *63*, 873−878.
(6) Hofstein, A.; Lunetta, V. N. *Rev. Educ. Res.* **1982**, *52*, 201−217.
(7) Hofstein, A.; Lunetta, V. N. *Sci. Educ.* **2004**, *88* (1), 28−54.
(8) Bennett, S. W.; O'Neale, K. *Univ. Chem. Educ.* **1998**, *2* (2), 58−62.
(9) Reid, N.; Shah, I. *Chem. Educ. Res. Pract.* **2007**, *8* (2), 172−185.
(10) Hawkes, S. J. *J. Chem. Educ.* **2004**, *81*, 1257.
(11) Rice, J. W.; Thomas, S. J.; O'Toole, P. *Tertiary Science Education in the 21st Century*; Australian Learning and Teaching Council, Ltd.: Sydney, Australia, 2009.
(12) Kerr, F. *Practical Work in School Science: An Account of an Inquiry into the Nature and Purpose of Practical Work in School Science Teaching in England and Wales*; Leicester University Press: Leicester, U.K., 1963.
(13) Buckley, J. G.; Kempa, R. F. *Sch. Sci. Rev.* **1971**, *53*, 24−36.
(14) Shulman, L. S.; Tamir, P. Research on Teaching in the Natural Sciences. In *Second Handbook of Research on Teaching*, Gage, N. L., Ed.; Rand McNally: Chicago, 1973; pp 1098−1148.
(15) Shymansky, J. A.; Penick, J. E. *Sci. Educ.* **1979**, *63*, 195−203.
(16) Johnstone, A. H.; Wood, C. A. *Educ. Chem.* **1977**, *14*, 11−12.
(17) Pavelich, M. J.; Abraham, M. R. *J. Chem. Educ.* **1979**, *56* (2), 100−103.
(18) Kirschner, P. A.; Meeser, M. A. M. *Higher Educ.* **1988**, *17*, 81−98.
(19) Johnstone, A. H.; Al-Shuaili, A. *Univ. Chem. Educ.* **2001**, *5* (2), 42−51.
(20) Carnduff, J.; Reid, N. *Enhancing Undergraduate Chemistry Laboratories, Pre-Laboratory, and Post-Laboratory Exercises, Examples and Advice*; Royal Society of Chemistry: London, 2003.
(21) Bruck, L. B.; Towns, M. H.; Bretz, S. L. *J. Chem. Educ.* **2010**, *87* (12), 1416−1424.
(22) Nakhleh, M. B.; Polles, J.; Malina, E. Learning in a Laboratory Environment. In *Chemical Education: Towards Research-Based Practice*; Gilbert, J. K., DeJong, L., Justi, R., Treagust, D. F., Van Driel, J. H., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002.
(23) Lincoln, Y. S.; Guba, E. G. *Naturalistic Inquiry*; Sage Publishers: Newbury Park, CA, 1985.
(24) The authors note that "status quo" is a conservative label for this group of faculty, some of whom might desire to make changes in laboratory instruction, but are not in a position to do so given the time and expense required to change laboratory instruction.
(25) Patton, M. Q. *Qualitative Research and Evaluation Methods*, 3rd ed.; Sage Publications: Thousand Oaks, CA, 2001.
(26) Strauss, A.; Corbin, J. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*, 2nd ed.; Sage Publications: Thousand Oaks, CA, 1998.