JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

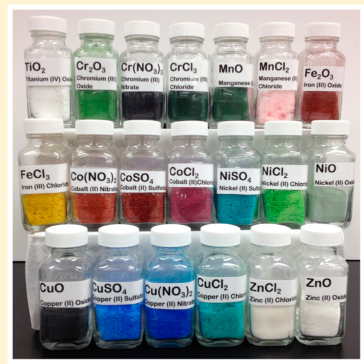
Transitioning from Expository Laboratory Experiments to Course-Based Undergraduate Research in General Chemistry

Ted M. Clark,* Rebecca Ricciardo, and Tyler Weaver

Department of Chemistry and Biochemistry, The Ohio State University, Columbus, Ohio 43210, United States

Supporting Information

ABSTRACT: General chemistry courses predominantly use expository experiments that shape student expectations of what a laboratory activity entails. Shifting within a semester to course-based undergraduate research activities that include greater decision-making, collaborative work, and "messy" real-world data necessitates a change in student expectations and epistemology. Design considerations for laboratories that transition students and teaching assistants from one format to another are described here along with experiences when implemented in the second semester of a large-enrollment general chemistry course.



KEYWORDS: *First-Year Undergraduate/General, Environmental Chemistry, Inorganic Chemistry, Laboratory Instruction, Inquiry-Based/Discovery Learning, Solid State Chemistry, Spectroscopy, TA Training/Orientation*

INTRODUCTION

In undergraduate chemistry curricula, the role and aims of laboratory instruction are important concerns.[1−3] Significant resources, both material and time, are committed to laboratories, and the list of proposed gains is far-reaching including making connections between the microscopic and macroscopic representations of matter, improving problem-solving skills, fostering critical thinking, and developing laboratory skills.[4]

In terms of meeting these objectives, it has been shown that practical work in lab is only weakly correlated with performance on paper-and-pencil tests and even when the seemingly same skills are assessed the achievement differs.[5] This may be due to the fact that paper-and-pencil tests are not able to measure student progress toward goals that are unique to laboratory experiences, such as understanding the complexity and ambiguity of empirical work,[4] and also that inadequacies may exist in current models of assessment of practical skills.[6] The claim that typical laboratory experiences help students improve content understanding because students directly interact with, observe, and manipulate materials has almost no evidence to support it, and the notion that concrete experiences with phenomena force students to confront their misunderstandings and re-evaluate their own assumptions also has very little support.[4]

Why are laboratory experiences less effective than hoped for? Although this is a complex question, the short answer may be that shortcomings of laboratory instruction reflect a mismatch between the instructional format of laboratory experiments and their objectives. For decades, the dominant laboratory instructional style has been expository laboratories in which the instructor defines the topic to be investigated, provides a context for the investigation, has students repeat instructions or follow them from a manual, and then compare results with a predetermined outcome known to both student and instructor.[7] This instructional style gives little emphasis to critical thinking and conceptual change, which is unfortunate given the current consensus that conceptual learning is the most important outcome of laboratory instruction.[8,9] It has been suggested that laboratory instructional style may affect learning, with a particular laboratory format being better suited for meeting a given goal. For example, conceptual learning may benefit from an inquiry-based or questioning approach, whereas skills are best taught by more direct instructional techniques.[9]

A relatively new but rapidly growing phenomenon has been the inclusion of in-class research experiences in large-enrollment introductory courses, such as general chemistry or biology, in an effort to produce gains for a large number of students similar to those associated with participation in research such as clarifying, confirming, or changing interest in a STEM career, intellectual and cognitive development, and development of research skills.[10−13] Programs like the Center for Authentic Science Practice in Education (CASPiE), the Research Experiences to Enhance Learning (REEL) project, the Freshman Research Initiative (FRI),[3,13−19] and others[20−23] have now included tens of thousands of students in research projects that replace traditional introductory laboratories in an exciting pedagogical shift aimed to broaden participation in

Published: November 5, 2015

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63

Table 1. Dimensions of Different Laboratory Learning Contexts[25]

Dimension	Action	Traditional	Transitional	CURE
Use of science practices	Students engage in...	Few scientific practices	Multiple scientific practices	Multiple scientific practices.
	Design and methods are...	Instructor defined	Instructor defined	Student or instructor defined
Discovery	Outcome is...	Known to students and instructors	Unknown to students	Unknown to students and instructors
Broader relevance or importance	Relevance of students' work...	Is limited to the course	Extends to CURE project	Extends beyond the course
Collaboration	Collaboration occurs...	(Infrequently) Among students	Among students	Among students, TAs and instructor
	Instructor's role is...	Instruction	Facilitation	Guidance and mentorship
Iteration	Risk of generating "messy" data are	Minimized	Present	Inherent

undergraduate research and better preparing the next generation of scientists.[24] Course-based undergraduate research experiences, or CUREs, offer the capacity to serve a very large number of students who invest time primarily in class and perform research in a teaching lab in comparison to a research internship model where a smaller number of self-selecting students invest time outside of class and work in a faculty research lab.[25]

CURE projects challenge students to think critically in inquiry investigations and work collaboratively to develop and investigate a research question of interest to the broader scientific community with an outcome unknown to students and instructors alike.[25,26] Often times, however, these are skills that have not been fostered in traditional expository laboratory experiments. Although richer laboratory experiences may be desirable, without proper preparation and instructional support, such a dramatic change may meet with resistance from both students and teaching assistants (TAs).[27] Effectively transitioning from "cook-book" laboratory experiments to CURE projects is therefore a crucial component in making in-class research projects "work". In this article, the design considerations of laboratory experiments for shifting from traditional laboratories to research projects in the areas of environmental chemistry and solid-state inorganic chemistry are described. CURE projects in these areas, as part of the REEL program in Ohio, have included several thousand participants at multiple institutions.[28] The transitional experiments described here are an important improvement and have been used for a large number ($n > 2300$) of general chemistry students participating in the REEL program at a single institution.

■ SETTING

In this general chemistry course at a large doctoral/research institution, the first semester laboratory experiments are expository, designated here as "traditional" due to their longstanding use at this institution and dominance in the general chemistry curriculum.[25,29] One TA supervises the work of 25 students during a 3-h session, and although TAs attend a weekly staff meeting, as first-year graduate students, they generally have not worked through an experiment prior to leading it. The lecture portion of the class is a large-enrollment offering (>300 students/instructor), and the degree to which laboratory topics are addressed varies by instructor. In lab, the students work independently to complete data collection, and data analysis and the writing of a laboratory report occur within the week following the lab. One activity, however, has a markedly different format as students work in small groups to investigate a computer simulation with an emphasis on discovery, model-building, and discussion of questions within the laboratory period and is therefore a precursor to the CURE laboratories.[30]

The second semester begins with ten traditional laboratory experiments followed by a dramatic shift as in-class research experiences in the areas of environmental chemistry or solid-state inorganic pigment synthesis comprise the final weeks of the course for all general chemistry students at this institution. Students in the environmental chemistry project ($n \approx 1100$) characterize different soil samples (urban soil from the area, topsoil, clay minerals, etc.) and study the soil's ability to retain different metal cations under a wide variety of conditions (pH, cations simultaneously adsorbed, etc.). This topic provides a rich parameter-space for creative investigations[31] with a close connection to, and relevance for, other scientific investigations.[32−34]

Students in the pigment synthesis project ($n \approx 1200$) design and synthesize potential new inorganic pigments. The materials are characterized with powder X-ray diffraction and the electronic transitions studied using UV−vis diffuse reflectance spectroscopy. The materials investigated are comparable to work carried out in other groups,[35,36] and these in-class projects in REEL have led to continued investigation by solid-state researchers.[37,38]

■ RATIONALE

Like other CUREs, the environmental and pigment synthesis projects integrate activities in a way that traditional laboratories do not (Table 1) and deviate sharply from experiments typically found in introductory courses.[29] The objective of the experiments described here is to transition students from the traditional laboratory experiences in which they have become ingrained to these more demanding ones. Success in meeting this objective is largely attitudinal, that is, are students willing to engage in an innovative laboratory framework with expanded expectations, or do they resist? In their investigation of college science innovations and the role of TAs in shaping and implementing these innovations, Seymour describes students as "accustomed to being rewarded for mechanical performances" who may respond with anxiety or protest when teachers "break from their role as knowledge distributors by using strategies that refocus attention on comprehension, exploration, discovery, or the connection and application of ideas" as this is a "breech of the implied classroom contract."[27] This is an apt characterization for the general chemistry students at this institution who are well aware of an implied classroom contract, having mastered laboratories that are "ritualistic" both in terms of what students do in lab (expository experiments, follow

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63

instructions) and what they do outside of lab (fill in data forms, submit lab reports) and that rewards students with grades based more on completion of tasks than on understanding.[27,39] Unsurprisingly, these students near the end of general chemistry report greater experience with scripted laboratories where they know the outcome, and laboratories or projects where only the instructor knows the outcome, than of laboratories or projects where no one knows the outcome (Table 2).[28] This is similar to undergraduates at other institutions enrolled in STEM classes prior to participating in a CURE project.[12]

Table 2. Student Self-Reported Preresearch Experience for Participants at This Institution and at Other Institutions (CURE Survey[12])[a]

Laboratory or Project	This Institution	Other Institutions
Scripted, students know outcome.	3.47	3.50
Only the instructor knows the outcome.	3.45	3.42
No one knows the outcome.	1.74	2.40
Students have input into process or topic.	2.40	2.80

[a]$N \approx 1500$. Five-point Likert scale: 5 = mastery, 1 = limited or no experience, average values shown.

A useful framework for understanding student willingness or anxiety when asked to take greater responsibility for their learning and do things like analyze authentic lab data, work with peers, or to construct an argument is to consider how these students view the nature and justification of human knowledge, that is, their personal epistemology.[40] In early stages of intellectual development, student reasoning is characterized by a basic duality in which knowledge can easily be divided into right and wrong statements, and the role of the student is to learn the right answers. In Perry's scheme of intellectual development, these students are Dualists. Dualists are common in general chemistry, along with multiplistic thinkers holding that some knowledge is "not yet known", and the role of learners is to find knowledge and to think for one's self.[41,42] Most traditional experiments support, but do not challenge, Dualists.[42]

It is problematic to ask Dualistic students to suddenly shift to a laboratory format that is too epistemologically advanced. Instead, providing support for Multiplists and challenges for Dualists is the goal.[42] This may include strategies like providing some flexibility in terms of content and sequencing, providing directions about how to generate problem solving strategies (or research questions), structuring group work and data analysis, and relying less on the instructor as a source of authority and more on peers and self.[42] Here, this CURE course is required in the curriculum, that is, students have not self-selected to participate in research; they are "nonvolunteers".[43] Although it has been noted, "a student will not enter into an undergraduate research experience unless she had a motive to do so",[12] and the motivation here is to complete a required class, and so the need to carefully design and then evaluate and improve the laboratory experience is heightened.

An awareness of student epistemology as a factor affecting student satisfaction of laboratory experiences is joined with the notion that student perceptions of the laboratory environment affect achievement and attitudes.[39,44] Student views of the clarity in which laboratory expectations and rules are communicated, whether work is conducted individually or as part of a team, and the material environment of the laboratory itself are all factors that account for significant differences in their content learning, attitudes, and science achievement.[44,45] Student perceptions of the laboratory environment have obvious epistemological underpinnings and are related to the instructional format of the experiment and the implied classroom contract as well. To the extent that traditional laboratories are viewed positively by general chemistry students, it is usually in terms of their rule clarity as student behavior is guided by formal rules and instructions.[4,28] The fact that traditional laboratories are *not* open-ended is viewed positively by some students and negatively by others,[46] a finding consistent with a population of both Dualistic and Mutliplistic thinkers.

Transitional laboratories in general chemistry must support Multiplists and challenge Dualists because these are the students found in general chemistry and also because many of the tasks and expectations of CUREs may cause anxiety for Dualists. The observation that if students are given too little guidance, some will feel overwhelmed, is understandable, especially for Dualists, as is student ignorance as to what research will be like.[47] Many expect scientific research to mimic their traditional laboratories, with emphasis on set procedures.[26] This ignorance may result in fear or uncertainty. A REEL student in an end-of-course survey voices such trepidation when stating "At the beginning, I was dreading this research project (since) I had never really experienced scientific research", and another remarks "Before (REEL), I had no opinion of research except one word: intimidating". Statements like these strongly speak to the need for transitioning students into the research portion of a CURE course, especially for a population of nonvolunteers.

■ DESIGN CONSIDERATIONS

Enthusiasm for CURE projects at the curricular-level is understood in terms of the range of benefits attributed to involvement in undergraduate research and the potential for broadening participation in research by including such experiences in introductory courses (see refs 10 and 12 for reviews). The extensive assessment of the REEL program during the period of 2006−2011 included questionnaires examining student perceptions of the teaching and learning practices ("what teachers do" and "what students do") comparing REEL and traditional courses, pre- and postcourse CURE surveys, examination of STEM retention data, *inter alia*.[28] Program benefits for students, such as an improved understanding of research, interest in seeking additional research opportunities, and persistence in a STEM discipline, were found comparable to other CURE programs.[26] Formative assessments, such as end-of-course surveys and focus-group discussions with students and TAs, in-lab observations, and analysis of student writing assignments, have continued to inform improvements leading to experiments like transitional laboratories. The complexity of undergraduate research makes the naming of benefits from participation in such activities a nontrivial task as undergraduate research engages a student's cognitive, behavioral, and attitudinal skills.[12] Indeed, many variables interact to influence student achievement and attitudes in laboratory experiences including traditional ones.[39] Ongoing formative assessment and a willingness to revise the laboratory framework to address shortcomings remain, however, important and ongoing concerns. As Seymour states, when describing other innovative STEM courses,

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63

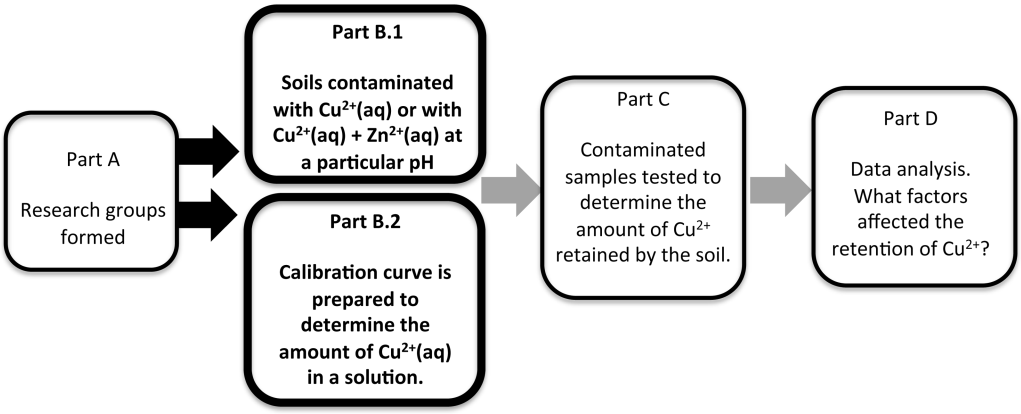


Figure 1. Progression of laboratory tasks in the experiment "Retention of Metal Cations".

"Faculty's chances of success in getting students to learn actively, responsibly, and effectively were increased when they understood the source of students' difficulties and directly addressed them in their materials and methods."[27] These transitional laboratories reflect our current understanding of how to address student difficulties as they begin a CURE project at this institution.

Design considerations for transitional laboratories are based on several factors such as epistemology, previous laboratory experiences, and the subsequent CURE project expectations in terms of dimensions like collaboration, scientific skills, and project-specific content knowledge. To move students from expository to CURE-style laboratories a discovery-based approach has been implemented. In these laboratories, the outcome is known in advance to the instructors (but not the students), and with the application of methods and procedures provided by the instructor, data are accumulated and examined inductively, leading to generalizations and hypotheses that may merit further investigation.[7,9] By using Brownwell's terminology, these transitional laboratories may be described as "Structured CUREs" with provided methods and a known answer, but with students taking the lead on data analysis and forming conclusions.[23] The placement of the project as a culminating experience in the course is deliberate, as students become confused when returned to a traditional format from an active one.[27] A few of the design features for transitional laboratories supporting this end-of-semester shift include signposting, the use of specific in-lab questions, and an inductive approach for introducing aspects of the research project.

Signposting

A critical requirement for success in the introduction of new materials and learning methods is "signposting" the project to provide students with a sense of direction and progress in their learning.[27] Innovative projects, including CUREs, are often "intellectual journeys" with student gaining mastery of key ideas, making conceptual linkages, and applying ideas in a variety of new situations. The story line intended to take students on this journey must be made clear by signposting its "structure, sequencing, major features, and linkages."[27] The CURE projects at this institution initially suffered from poor signposting, as evidenced by a student participating early in the program remarking, "I never knew exactly what the final product was going to be before it was turned in. If we could receive an outline of the general overview of our REEL project, I feel a lot of confusion could have been avoided."

For these CURE projects, signposting in a transitional lab includes communicating, in general terms, the overarching research question, for example, "What affects the retention of metal cations by soil", and the reasons why a project interests the scientific community, such as "There is a need to find new, less toxic, and less expensive alternatives to commercial pigments" is also shared. Clearly communicating the macro-research question is important, as is the idea that student-generated research questions will be part of a larger framework, since these support the iterative-dimension of CURE projects with findings built upon year-to year and also show students the relevance of their work to a broader scientific community.

Signposting also entails conveying the tasks in the transitional lab itself. In the environmental chemistry experiment "Retention of Metal Cations", groups contaminate different types of soil (organic, sand, vermiculite) with $Cu^{2+}(aq)$ and $Cu^{2+}(aq)$ + $Zn^{2+}(aq)$ solutions at different pH. A UV–vis spectrophotometer is used to construct a calibration curve for the copper amine complex, and then the filtrate from the contaminated samples is treated with ammonium hydroxide and the concentration of copper in solution determined spectrophotometrically. In the data analysis, the percentage of copper retained in a particular test is calculated (see Supporting Information for the experiment and instructor notes). In the experiment "Preparation of Colored Pigments", different solid transition metal compounds are examined and classified in terms of color, number of d-electrons, and oxidation number. Generalizations are then made as to what factors affect a compound's color. These initial hypotheses lead to research questions investigated by selecting transition metals to be dopants in host compounds and are synthesized using solid-state techniques.

For these laboratories, signposting is supported by flowcharts within the manual illustrating the experiment's progression. Some aspects of time management are also included. For example, aspects of the lab that may be performed simultaneously are shown to prompt students to divide tasks among group members (Figure 1). Flowcharts are not simply shown at the start of the experiment but instead repeated as groups move through the experiment and the overall project. Signposting is also relevant for TAs as their familiarity with an experiment's story line on multiple levels, that is, logistical, conceptual, and pedagogical, and an ability to repeatedly

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56–63

communicate this information with their students, is fundamental for achieving the laboratory learning goals.

In-Lab Questions

During the laboratory period, students continue the standard practice of recording information in a laboratory notebook. However, transitional laboratories include questions in various formats that students discuss in small groups and answer in the lab manual throughout the period. Some in-lab questions move students through the lab story line, whereas others have students make connections with content from lecture or previous laboratories. Questions are designed to elicit conversation and "thoughtful questions" from students[41] as they interact with each other and the TA since verbal interactions among students working in a group and between the group and their instructor is an integral aspect of laboratory activity.[48]

Since REEL's inception, a dramatically different laboratory dynamic was noted between REEL and non-REEL courses. An early participant with REEL described their contrasting experiences when observing "Usually chemistry lab is just a scary place where no one talks to each other for the whole quarter, but this lab is definitely not like that. I could just tell the difference in the room when we were doing a (REEL) lab, whereas during a lab out of the notebook, the room was completely quite and boring." Another student commented, "The aspects of the program I enjoyed were working together with a group and forming a hypothesis. It was very interesting to work with a group who came from many different experiences to see what everyone can bring to the table." This comment may be understood epistemologically in that a Dualist does not view peers as legitimate sources of knowledge. To a Multiplist, peers are not authorities but can be legitimate in finding the truth, which is what occurs in CURE laboratories.

Discussion between students, and between students and TAs, although recognized as valuable parts of REEL from the beginning, varied greatly between lab sections with different TAs in terms of frequency and depth. The best conversations occurred in lab sections where the TA understood the importance of questioning students (rather than providing answers) and when they were skilled at both asking questions and recognizing opportunities for encouraging group discussion. The format of transitional laboratories includes questions placed throughout the manual in an effort to address these points. This is necessary as traditional laboratory discourse, wherein the student independently seeks direct instructions from their TA, is out of circulation for the duration of the CURE laboratories, being replaced by a new group dynamic with conversations among peers being supported by the TA.

These transitional experiments also lead to data sets challenging students to identify meaningful variation for results that edge the students toward the "messiness of real-world data" they may encounter in CURE projects. Inductive generalizations are made and used to address research claims. To scaffold this process, initial claims are provided along with suggested supporting evidence. Then, students provide their own research claims paired with supporting evidence. In both experiments, these analyses led to active group discussions facilitated by TAs.

As part of their training for CURE laboratories, TAs first completed the transitional lab they would be teaching. This began by having TAs form groups and directing them to act as students. In "student-mode", the TAs then worked through the experiment, answered questions, talked with each other, analyzed data, and responded to questions posed by course instructor, all the while acting as they held a typical student would behave. This was followed by a debriefing (now as teachers) in which they provided feedback and discussed pros and cons of the laboratory format. In this way, TAs gained an understanding of their role in the laboratory and also insights in to what their students would experience. Placing teachers in student-mode during training is a strategy adopted from the modeling community.[49] Its strengths include encouraging participation, allowing teachers to ask questions without threatening their expertise, and prompting reflection on their own classroom practices. In the context of these experiments, TAs experienced how the instructor's questioning supported group discussions with students taking greater responsibility for their own learning. With these insights, TAs gained confidence in supporting discussions in their own classes for the *same* questions. For TAs with limited experience asking questions and fostering group discussion, this framework was reassuring as they could see "what the instructor wanted".

Graduate TAs new to their program are often assigned to general chemistry. These TAs are close in age to the students they are teaching and are especially concerned with authority and control issues and with being seen as competent in that they can answer students' questions.[50] As such, they may resist behaviors that encourage engagement of students in more meaningful ways, such as responding with questions that help students make progress without making decisions for them,[39] if these actions no longer position the TA as the dispenser of information.[27] In traditional laboratories, the TA provides instructions, especially logistical ones involving time management or lab technique, and student questions are focused on laboratory mechanics like completing prescribed tasks and identifying which data to record and where to record them.[48] Questions posed by TAs are usually about the students' experiences ("What did you do...?" or "What happened when you...?"). In CURE laboratories, the TA's questions are ones of application, requiring students to use knowledge in new contexts ("What evidence do we have that supports...?") and also explanation ("What justification can be provided for...?").[51] For both students and TAs asked to change their own roles and behaviors during laboratory activities, transitional laboratories with numerous predefined questions support this shift.

Introduction to a Research Project

Another important design consideration that has evolved with REEL laboratories is the manner in which students begin their in-class research experience. Initially, in the REEL program at this institution, students "got started" with research projects by reading extensive background information particular to their project. For example, to better understand factors affecting the color of transition metal compounds, students were first given information on crystal field theory, molecular orbital theory, and metal-to-ligand charge transfer bands. This large quantity of primarily theoretical background information was included in the laboratory manual and then verified in expository laboratories with limited inquiry. Front-loading information like this, or having students delve into primary sources to begin their project, is not an unusual approach for introducing students to a research area[52] but was found to be less suitable for a required course that included a CURE project. Ambitious in terms of introducing advanced topics, this approach

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63

discouraged students less interested in the material or less prepared academically. Like other innovative classes, the workload also increased and became more demanding in terms of time and effort. This led to resistance by students who felt they now had to work harder and become more engaged than what they had bargained for.[27] In fairness to the students, the end of the school year is when many courses use large-scale culminating assignment. As a student noted, "I disliked how we had to spend a lot of time outside of class...I am in a group for my engineering class too, and meeting for both was very difficult to incorporate into my schedule. Chemistry is not my only class with a heavy workload."

The transitional laboratories now are thematically the same but very different in format from these earlier CURE projects. Instead of providing a large amount of advanced information to begin the project that only serves a subset of students, groups now collaboratively generate their own initial understandings, which they then support with evidence during the lab period. More advanced topics, such as crystal field theory, UV−vis reflectance spectroscopy, or the structure of clay minerals, are now introduced later in the project. Once again, these concepts are investigated in lab rather than with additional reading assignments.

An interesting observation is that after having analyzed their data and supported claims with evidence, students at the end of a transitional lab were often found to then seek theoretical explanations. For example, in the environmental project, students conclude that sand poorly retains metals cations and that pH affects retention for clay minerals. Many students would then ask their TAs to explain these phenomena at the end of the lab period. The TAs, at this point in the course story line, were advised to leave the question unresolved as this very topic was investigated in the next experiment. It should be noted, however, that many TAs had difficultly withholding information at this point as their desire to provide students with answers and demonstrate their expertise trumped the pedagogical rationale of student discovery that was still new to them.

■ DISCUSSION

Some insights as to whether transitional laboratories meet the objective of transitioning students from traditional laboratory experiences to more demanding CURE projects may be gained by considering student experiences with the overall project. We have found a valuable end of project question in the REEL program is simply "Would you recommend a general chemistry student take a REEL course", as participants provide insights into the program's strengths and shortcomings.[28]

A recurring finding in end-of-project surveys is that students recognize they must become more responsible for their own learning in a CURE course. As a student states, "I liked that this project made me think. It wasn't like a traditional lab where everything was given to me and all I had to do was follow the steps. It required me to know exactly what I was doing and understand the concepts." For some students, this awareness leads to a less positive recommendation, or as a student states "It depends more on their personality. If they are more the type to blindly follow directions, then do not (enroll in REEL), but if they are getting sick of just working out of the book, then I would advise them to get into the REEL class."

Overall, about 85% of students in the most recent REEL laboratories that included these transitional laboratories recommended participation in REEL. In comparison, about 70−75% of students in the first REEL laboratories recommended participation. Given the scale of implementation at this institution (n > 2200/year), this represents a significant increase in the number of students having a positive experience in a CURE course each year.

As discussed throughout this article, CURE experiments place different demands on students and also different demands on TAs. The relationship between student perceptions of the course and their view of their TAs helpfulness is shown in Figure 2. Overall, the TAs are viewed quite positively by their students. As might be expected, students with the most positive views of their TA recommended REEL most strongly (87%). Also noteworthy, however, is that students with the most negative views of their TAs also strongly recommended REEL (82%). Although more work is needed to understand how TAs influence overall student satisfaction in a CURE course, it appears that while they may be an important factor, other aspects of the course are also important. For example, students in this program identify the project's open-endedness, group cohesiveness, and connection to lecture content (particularly for the pigment project) as strong positives. In terms of transitional laboratories, it was found that negative perceptions of rule clarity and workload have both diminished, a finding understood in terms of design considerations for these revised laboratories.

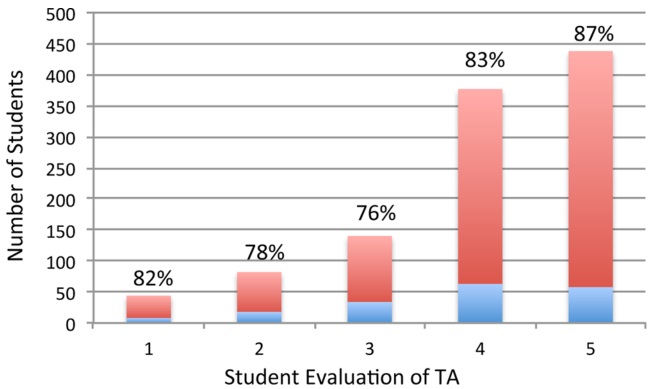


Figure 2. Students recommending participation in a REEL course ("yes" shown in red and as percentage, "no" in blue) and their view of their laboratory TA (five-point Likert scale: 5 = very helpful, 1 = not helpful) following completion of the environmental research project.

Transitional laboratories are based on design considerations that can inform other laboratory activities aiming to move beyond expository laboratories. What the students transition "to" is quite open-ended. For example, like previous REEL experiments,[53] these transitional laboratories are currently being modified for use in high school AP courses. Environmental chemistry and solid-state inorganic chemistry are themes often addressed in capstone projects in general chemistry, and the need to transition students to these laboratory experiences is also germane.

Finally, the design considerations informing these transitional laboratories reflect the collective experience of instructors that have worked with an enormous number of general chemistry students in CURE laboratories for nearly a decade. Initial questions regarding the sustainability of CURE laboratories have been replaced by questions of their efficacy given their rapid adoption in chemistry, biology, and other STEM fields. New laboratory contributions, such as the laboratories

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63

proposed here, show the continued evolution of these laboratories and the significant impact they are having on general chemistry instruction nationwide.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00371.

Laboratory documentation, student instructions (PDF, DOCX)
Instructor notes (PDF, DOCX)
Laboratory documentation, student instructions (PDF, DOCX)
Instructor notes (PDF, DOCX)
Laboratory schedule for this course (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

*E-mail: clark.789@osu.edu.

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Hofstein, A. The laboratory in chemistry education: thirty years of experience with developments, implementation, and research. *Chem. Educ. Res. Pract.* **2004**, *5* (3), 247–264.
(2) Hofstein, A.; Lunetta, V. N. The laboratory in science education: Foundations for the twenty-first century. *Sci. Educ.* **2004**, *88* (1), 28–54.
(3) Elliott, M. J.; Stewart, K. K.; Lagowski, J. J. The role of the laboratory in chemistry instruction. *J. Chem. Educ.* **2008**, *85* (1), 145–149.
(4) *America's Lab Report: Investigations in High School Science*; Schweingruber, H. A., Hilton, M. L., Singer, S. R., Eds.; National Academies Press: Washington, DC, 2005.
(5) Research on Using Laboratory Instruction in Science. In *Handbook of Research on Science Teaching and Learning Project*; Gabel, D. L., Ed.; Macmillan Publishing Company: New York, 1993.
(6) Bennett, J. Practical work at the upper high school level: the evaluation of a new model of assessment. *International Journal of Science Education* **2001**, *23* (1), 97–110.
(7) Domin, D. S. A review of laboratory instruction styles. *J. Chem. Educ.* **1999**, *76* (4), 543–547.
(8) Abraham, M. R.; Craolice, M. S.; Graves, A. P.; Aldhamash, A. H.; Kihega, J. G.; Gal, J. G. P.; Varghese, V. The nature and state of general chemistry laboratory courses offered by colleges and universities in the United States. *J. Chem. Educ.* **1997**, *74* (5), 591–594.
(9) Abraham, M. R. What can be learned from laboratory activities? Revisiting 32 years of research. *J. Chem. Educ.* **2011**, *88* (8), 1020–1025.
(10) Seymour, E.; Hunter, A. B.; Laursen, S. L.; DeAntoni, T. Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study. *Sci. Educ.* **2004**, *88* (4), 493–534.
(11) Hunter, A. B.; Laursen, S. L.; Seymour, E. Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development. *Sci. Educ.* **2007**, *91* (1), 36–74.
(12) Lopatto, D.; Tobias, S. *Science in Solution: The Impact of Undergraduate Research on Student Learning*; Council on Undergraduate Research: Washington, DC, 2010.
(13) Harrison, M.; Dunbar, D.; Ratmansky, L.; Boyd, K.; Lopatto, D. Classroom-based science research at the introductory level: changes in career choices and attitude. *CBE-Life Sciences Education* **2011**, *10* (3), 279–286.
(14) Weaver, G. C.; Russell, C. B.; Wink, D. J. Inquiry-based and research-based laboratory pedagogies in undergraduate science. *Nat. Chem. Biol.* **2008**, *4* (10), 577–580.
(15) Russell, C. B.; Weaver, G. C. A comparative study of traditional, inquiry-based, and research-based laboratory curricula: impacts on understanding of the nature of science. *Chem. Educ. Res. Pract.* **2011**, *12* (1), 57–67.
(16) Szteinberg, G. A.; Weaver, G. C. Participants' reflections two and three years after an introductory chemistry course-embedded research experience. *Chem. Educ. Res. Pract.* **2013**, *14* (1), 23–35.
(17) Clark, T. M. A Statewide Initiative for Engaging Undergraduates in Chemical Research. In *Broadening Participation in Undergraduate Research*; Boyd, M. K., Wesemann, J. L., Eds.; Council on Undergraduate Research: Washington DC, 2009; pp 121–125.
(18) Clark, T. An Ambitious Statewide Transformation of Introductory Chemical Courses: Assessing the Ohio Consortium for Undergraduate Research—Research Experiences To Enhance Learning (OCUR-REEL) Project. In *Assessment of Chemistry. Assessment in the Disciplines*; Ryan, J., Clark, T., Collier, A., Eds.; Association for Institutional Research: Tallahassee, FL, 2010; Vol. 5, pp 7–26.
(19) Simmons, S. One institution's approach: How the University of Texas at Austin merges research and teaching through the Freshman Research Initiative. *FASEB J.* **2014**, *28* (1), 93–101.
(20) Ford, J. R.; Prudente, C.; Newton, T. A. A model for incorporating research into the first-year chemistry curriculum. *J. Chem. Educ.* **2008**, *85* (7), 929–933.
(21) Tomasik, J. H.; Cottone, K. E.; Heethuis, M. T.; Mueller, A. (2013). Development and preliminary impacts of the implementation of an authentic research-Based experiment in General Chemistry. *J. Chem. Educ.* **2013**, *90* (9), 1155–1161.
(22) Winkelmann, K.; Baloga, M.; Marcinkowski, T.; Giannoulis, C.; Anquandah, G.; Cohen, P. Improving Students' Inquiry Skills and Self-Efficacy through Research-Inspired Modules in the General Chemistry Laboratory. *J. Chem. Educ.* **2015**, *92*, 247–255.
(23) Brownell, S. E.; Kloser, M. J.; Fukami, T.; Shavelson, R. Undergraduate biology lab courses: comparing the impact of traditionally based "cookbook" and authentic research-based courses on student lab experiences. *J. Coll Sci. Teach* **2012**, *41* (4), 36–45.
(24) Brownell, S. E.; Kloser, M. J. Toward a conceptual framework for measuring the effectiveness of course-based undergraduate research experiences in undergraduate biology. *Studies in Higher Education* **2015**, *40* (3), 525–544.
(25) Auchincloss, L. C.; Laursen, S. L.; Branchaw, J. L.; Eagan, K.; Graham, M.; Hanauer, D. I.; Dolan, E. L.; et al. Assessment of course-based undergraduate research experiences: a meeting report. *CBE-Life Sciences Education* **2014**, *13* (1), 29–40.
(26) Linn, M. C.; Palmer, E.; Baranger, A.; Gerard, E.; Stone, E. Undergraduate research experiences: Impacts and opportunities. *Science* **2015**, *347* (6222), 1261757.
(27) Seymour, E. *Partners in Innovation: Teaching Assistants in College Science Courses*; Rowman & Littlefield: Lanham, MD, 2005.
(28) Kahle, J. B.; Li, Y. *Evaluation of Research Experiences To Enhance Learning: Final Report*; Miami University, Ohio's Evaluation & Assessment Center for Mathematics and Science Education: Oxford, OH, 2011.
(29) Domin, D. S. A content analysis of general chemistry laboratory manuals for evidence of higher-order cognitive tasks. *J. Chem. Educ.* **1999**, *76* (1), 109–111.
(30) Clark, T. M.; Chamberlain, J. M. Use of a PhET Interactive Simulation in General Chemistry Laboratory: Models of the Hydrogen Atom. *J. Chem. Educ.* **2014**, *91* (8), 1198–1202.
(31) Clark, T. M. Fostering Creativity in Undergraduate Chemistry Courses with In-Class Research Projects. In *Creativity and Innovation Among Science and Art*; Charyton, Ed.; Springer-Verlag: London, 2015; pp 113–134.
(32) Fontes, M. P. F.; Gomes, P. C. Simultaneous competitive adsorption of heavy metals by the mineral matrix of tropical soils. *Appl. Geochem.* **2003**, *18* (6), 795–804.

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56–63

(33) Gomes, P. C.; Fontes, M. P.; da Silva, A. G.; de S Mendonça, E.; Netto, A. R. Selectivity sequence and competitive adsorption of heavy metals by Brazilian soils. *Soil Sci. Soc. Am. J.* **2001**, *65* (4), 1115−1121.
(34) Covelo, E. F.; Vega, F. A.; Andrade, M. L. Simultaneous sorption and desorption of Cd, Cr, Cu, Ni, Pb, and Zn in acid soils: II. Soil ranking and influence of soil characteristics. *J. Hazard. Mater.* **2007**, *147* (3), 862−870.
(35) Smith, A. E.; Mizoguchi, H.; Delaney, K.; Spaldin, N.; Sleight, A. W.; Subramanian, M. A. Mn^{3+} in Trigonal Bipyramidal Coordination: A New Blue Chromophore. *J. Am. Chem. Soc.* **2009**, *131* (47), 17084−17086.
(36) Tamilarasan, S.; Sarma, D.; Bhattacharjee, S.; Waghmare, U. V.; Natarajan, S.; Gopalakrishnan, J. Exploring the Color of Transition Metal Ions in Irregular Coordination Geometries: New Colored Inorganic Oxides Based on the Spiroffite Structure, $Zn_{2-x}M_xTe_3O_8$ (M = Co, Ni, Cu). *Inorg. Chem.* **2013**, *52* (10), 5757−5763.
(37) Dolgos, M. R.; Paraskos, A. M.; Stoltzfus, M. W.; Yarnell, S. C.; Woodward, P. M. The electronic structures of vanadate salts: Cation substitution as a tool for band gap manipulation. *J. Solid State Chem.* **2009**, *182* (7), 1964−1971.
(38) Dey, S.; Ricciardo, R. A.; Cuthbert, H. L.; Woodward, P. M. Metal-to-metal charge transfer in AWO_4 (A = Mg, Mn, Co, Ni, Cu, or Zn) compounds with the wolframite structure. *Inorg. Chem.* **2014**, *53* (9), 4394−4399.
(39) Lunetta, V. N.; Hofstein, A.; Clough, M. P. Learning and teaching in the school science laboratory: An analysis of research, theory, and practice. *Handbook of Research on Science Education* **2007**, 393−441.
(40) Hofer, B. K. Personal epistemology research: Implications for learning and teaching. *Educational Psychology Review* **2001**, *13* (4), 353−383.
(41) Winberg, T. M.; Berg, C. A. R. Students' cognitive focus during a chemistry laboratory exercise: Effects of a computer simulated prelab. *J. Res. Sci. Teach.* **2007**, *44* (8), 1108−1133.
(42) Finster, D. C. Developmental Instruction. Part II. Application of the Perry Model to General Chemistry. *J. Chem. Educ.* **1991**, *68* (9), 752−756.
(43) Kloser, M. J.; Brownell, S. E.; Shavelson, R. J.; Fukami, T. Effects of a research-based ecology lab course: a study of nonvolunteer achievement, self-confidence, and perception of lab course purpose. *J. Coll Sci. Teach* **2013**, *42*, 90−99.
(44) Fraser, B. J. Classroom learning environments. *Handbook of research on science education* **2011**, 103−124.
(45) Henderson, D.; Fisher, D.; Fraser, B. Interpersonal behavior, laboratory learning environments, and student outcomes in senior biology classes. *J. Res. Sci. Teach.* **2000**, *37* (1), 26−43.
(46) Tsai, C. C. Relationships between student scientific epistemological beliefs and perceptions of constructivist learning environments. *Educational Research* **2000**, *42* (2), 193−205.
(47) Newton, T. A.; Tracy, H. J.; Prudenté, C. A research-based laboratory course in organic chemistry. *J. Chem. Educ.* **2006**, *83* (12), 1844.
(48) Krystyniak, R. A.; Heikkinen, H. W. Analysis of verbal interactions during an extended, open-inquiry general chemistry laboratory investigation. *J. Res. Sci. Teach.* **2007**, *44* (8), 1160−1186.
(49) *American Modeling Teachers Association*. https://modelinginstruction.org/ (accessed August 2015).
(50) Robinson, J. B. New Teaching Assistants Facilitate Active Learning in Chemistry Laboratories: Promoting Teaching Assistant Learning through Formative Assessment and Peer Review. *Journal of Graduate Teaching Assistant Development* **2000**, *7* (3), 147−62.
(51) Penick, J. E.; Crow, L. W.; Bonnstetter, R. J. Questions are the answer. *Science Teacher* **1996**, *63* (1), 26.
(52) Procko, K.; Simmons, S. L. Research as an introductory course: Engaging first-year students in authentic chemistry research through the Freshman Research Initiative program. In *Developing and Maintaining a Successful Undergraduate Research Program*; Chapp, T. W., Benvenuto, M. A., Eds.; American Chemical Society: Washington, DC, 2013.
(53) Clark, T. M.; Urig, B. Project REEL in Advanced Placement Chemistry. *CERMACS (Central Regional Meeting of the American Chemical Society)*; Case Western Reserve: Cleveland, OH, 2009.

DOI: 10.1021/acs.jchemed.5b00371
J. Chem. Educ. 2016, 93, 56−63