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Application of a Cognitive Task Framework to Characterize Opportunities for Student Preparation for Research in the Undergraduate Chemistry Laboratory

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ABSTRACT: Undergraduate chemistry laboratory instruction can be considered from many perspectives and addresses multiple educational aims. We critically assess an inventory of "Cognitive Tasks of Experimental Research" for its applicability to chemistry laboratory teaching, and then apply it to an integrated upper-level laboratory course as an example subject. We note patterns in the prevalence of different cognitive tasks in the course, including: a paucity of tasks related to determining research goals, evaluating experiment feasibility, and experimental design; and differences between cognitive task prevalence in organic chemistry experiments versus those in other subdisciplines of chemistry. We emphasize that this cognitive tasks of experimental research perspective provides multiple ways to consider the chemistry laboratory curriculum, and we discuss implications for practice. The work contributes to the debate about the role and aims of laboratory instruction in chemistry, and provides a tool to chemistry educators with which to reflect upon their practice and curriculum in laboratory education.

KEYWORDS: *Upper-Division Undergraduate, Laboratory Instruction, Cognitive Tasks, Undergraduate Research, Curriculum*

INTRODUCTION

What should be learned in chemistry undergraduate laboratory courses? If you are solely interested in chemical concepts, this question might be answered by perusing the experiment titles of laboratory manuals to understand the breadth of content taught. However, it should also be considered holistically. Kirschner and Meester[1] identified 120 possible objectives for the instructional chemistry laboratory, and numerous other authors have commented on its role (see refs 2−4 and references therein).

With such complexity in the laboratory teaching environment, it is no surprise that many approaches to understanding and evaluating laboratory courses have been described, each bringing a different perspective. These include studies of the course goals that faculty have,[5−7] of student goals,[8,9] and of teaching practices and norms for specific courses.[10−13] Further, Domin[14] analyzed chemistry laboratory curricula according to levels of thinking skills as presented in Bloom's Taxonomy of educational objectives, while Fay et al. developed a rubric to characterize the level of inquiry in chemistry experiments.[15,16] We describe a further approach based on consideration of Cognitive Tasks of Experimental Research (CTERs). CTERs are types of thinking conducted by professional researchers of experimental chemistry. The approach is rooted in the notion that analysis of the activities and/or thought processes of experts should be used to inform teaching, and that deliberate practice is a means to develop expertise.[17,18] In other words, for laboratory courses to prepare students to be effective experimentalists, the tasks in which expert experimental researchers engage must be identified, and course activities designed to allow students to practice them.

Task analysis dates to the late 1800s (see ref 19). Traditionally it was used to identify the manual *actions* of employees, with the goal of increasing industrial efficiency through faster training of new employees and better assessment of employee performance. *Cognitive* Task Analysis (CTA) describes the process of inventorying the *knowledge and thought processes* involved in completing certain tasks.[20−22] CTA is widely used, especially to inform training for roles that involve complex decision-making, for example in air-traffic control, law enforcement, or medicine.[22]

CTA has been used to inform the development of teaching strategies and materials, including in science and mathematics. Greeno[23] used CTA as a framework for studying learning of arithmetic and geometry by elementary school students and examined how teachers directly or indirectly presented certain processes. Feldon[24] suggested use of CTA results in the development of more effective instructional materials for teaching students to mimic the instructor's own problem-solving approaches, compared with materials developed from the instructor's recollection of their strategies. Further work showed that undergraduate students in a biology laboratory were less likely to withdraw from the course and wrote more sophisticated laboratory reports when teaching materials derived from CTA were used instead of "traditional" instructional approaches.[25] A 2013 meta-analysis[26] of CTA use in a variety of forms of training concluded that the "information

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Table 1. List of Cognitive Tasks of Experimental Physics Research[a]

Cognitive Tasks of Experimental Research in Physics
1. Establishing research goal: What are the goal(s) and question(s) of the research?
a. Deciding if the goal is interesting, timely, worthwhile, etc.
b. Predicting if the goal is sufficiently ahead of current knowledge to be interesting but not so far ahead that it might have too high a risk of failing or be ignored.
c. Evaluating whether the research question is consistent with the constraints on funding, time, equipment, and laboratory capacity, including personnel.
2. Defining criteria for suitable evidence: Deciding what will constitute suitable evidence to achieve the goal by developing and/or utilizing existent criteria:
a. What data would be convincing given the state of the field?
b. What variables are important and how might they be measured and controlled?
c. What types of experimental controls and checks would need to be in place?
3. Determining feasibility of experiment
a. Predicting whether or not it is realistically possible to carry out the experiment, and, if it is, analyzing the scale of time and money required and deciding if these are reasonable. (This involves a more detailed reiteration of 1.c.)
b. The researcher must also analyze contingency options, if the results of the experiment are not what is hoped for. Will the data produced still provide novel publishable information? Will the results show how to improve the apparatus to achieve conditions needed to obtain hoped-for results?
4. Experimental design
a. Exploration of many possible preliminary designs (requires clear definition of the optimum depth of analysis of the alternative designs).
b. Analyzing relevant variables that may lead to systematic errors in results and interpretation. This requires having complex cause and effect models for the experiment. (Will be repeated after measuring performance of the apparatus.)
c. Finalizing the design, taking into account construction details and performance requirements of each component. Often requires bringing in additional expertise.
d. Developing detailed data acquisition strategy: How much data to take and over what parameter ranges, how long to accumulate data in each measurement, in what order are things measured, which measurements do you repeat and how often? Deciding on required precision and accuracy: This includes deciding which quantities need not be measured. This must take into account constraints on time, clarity of results, all potential statistical and systematic uncertainties, and the importance and requirements for distinguishing between different potential interpretations of results. (This step is repeated/revised after performance of apparatus has been measured.)
*5. Construction and testing of apparatus**,**
a. Deciding who should build the various parts and on what schedule (in-house, purchase standard parts, special construction by outside companies, etc.). Requires evaluation and application of trade-offs of cost, construction expertise, time, degree of confidence as to specific design details.
b. Developing criteria and test procedures for evaluation of the apparatus components as they are completed.
c. Collecting data on performance of specific components and full apparatus.
d. Developing procedures for tracking down the source of malfunction when the individual components or the assembled apparatus do not perform as designed. This necessarily involves deep familiarity with the respective hardware and a repertoire of troubleshooting regimes that are highly specific to the field, the apparatus, and the approach being used.**
e. Figuring how to modify particular parts, or overall apparatus, as needed according to test results.
f. Reiterate data acquisition strategy 4.d., taking into account actual performance of finished apparatus.
g. After completion, collecting experimental data.
6. Analyzing data
a. Modeling the data by suitable mathematical forms, including deciding which approximations are justified and which are not.
b. Deciding on what statistical analysis methods and procedures are appropriate.
c. Calculating the statistical uncertainty.
d. Calculating the systematic uncertainties as needed (often already done as part of the data acquisition strategy).
*7. Evaluating results**,**
a. Checking the results, when they come out differently than expected. This involves calling on complex mental models incorporating a web of cause and effect relationships, strategies for separating relevant and irrelevant information, complex pattern recognition and search algorithms. (Also usually involves extensive additional data collection, and possible modification of apparatus and redoing data collection.)
b. Testing data that come out as expected. Identify redundant tests for possible systematic errors, being particularly sensitive to experimenter biases.
8. Analyzing implications if results are novel and/or unexpected and confirmed
a. What are plausible interpretations or new theoretical or experimental directions implied by these results?*
9. Presenting the work
a. Follow standard data display procedures or, as needed, develop new procedures that highlight critical features of methods or results.
b. Explain the work so the broader context and uniqueness of the work, the apparatus, the procedures, and the conclusions are easily understood, and the audience/readers perceive it to be of maximum interest and significance.

[a] Reproduced with permission from ref 28. Copyright (2015) American Association of Physics Teachers. Notes * and ** are from the original. *Requires extensive expertise in the research field. **Requires extensive experience with the relevant equipment.

elicited through CTA provides a strong basis for highly-effective instruction" (p. 293). Elsewhere, consideration of the cognitive tasks required of physics researchers guided the transformation of a fourth-year optics course, a transformation which involved replacing lectures with classroom activities and which resulted in a 15% improvement in exam marks.[27]

Wieman[28] published an inventory of cognitive tasks for the role of experimental physics researcher, identifying 29 cognitive tasks across nine categories (see Table 1). This inventory resulted from Wieman's reflection on his experience as a successful experimental researcher in physics. Holmes and Wieman[29] used it to explore the cognitive tasks encountered in undergraduate physics programs. That study suggested certain cognitive tasks were often encountered in undergraduate research experiences, but only rarely in laboratory or lecture-based courses. Follow-up work coded student decision-making in first-year physics laboratories.[30] Twelve categories that parallel a subset of Wieman's CTERs were used in that study; students in an intervention lab course, which offered increased decision-making opportunities, showed increased adoption of expert-like practices.

Within chemistry education, Carmel et al.[31] characterized two extremes of first year laboratory curricula using a modified version of the American National Research Council's inventory of science practices.[32] Carmel's work assessed how often students engaged in these practices, comparing a traditional general chemistry laboratory and a laboratory that adopted a cooperative, project-based philosophy. Further, the work identified which parts of laboratory teaching (e.g., prelab, in-lab, or postlab reporting) most often allowed students to experience inquiry[15] learning activities. The project-based curriculum engaged students more frequently with science practices and the practices were more widespread.[31] A related work describes the development of activities that may assess student proficiency at applying four of the science practices.[33] Although specific to the general chemistry laboratory in level and content, the activities do not appear to require in-laboratory work.

Undergraduate research (e.g., final year projects or theses) can be considered the opposite end of laboratory experience from the general chemistry laboratory. While not all chemistry graduates will embark upon a career in research, it is still worthwhile to consider the extent to which undergraduate laboratory courses prepare students to engage in the cognitive tasks associated with experimental research. Upper-level laboratory courses are often the final structured instructional lab experience for students before they engage in research projects within a professional laboratory. As such, preparation for experimental research is a commonly stated learning outcome in lab curricula. Work exploring this perspective directly is, however, rare. Although the role and goals of the chemistry laboratory from the viewpoints of upper-level students,[9] faculty,[5−7] and both students and faculty[34] have been studied, only one of these works explicitly identified preparation for research as important[7] (though many of the roles and goals identified in the other studies are not incompatible with such preparation). This article complements literature on the role and aims of laboratory instruction by viewing chemistry laboratory education from a specific preparation-for-research angle. We analyze the CTERs present in an upper-level, integrated chemistry laboratory course in an exploratory fashion. We describe how the CTERs in the course were assessed and what was found, before rationalizing the findings and describing the implications for teaching that resulted both from undertaking the process and by examining its outcomes.

■ CONTEXT

The upper-level laboratory course used here as an illustrative example is offered at the University of British Columbia, a large, research-intensive, publicly funded, Canadian university. Third-year students in chemistry and biochemistry degree programs take the course, as well as those registered in a general sciences program.

The course was recently redesigned as a standalone experience, integrating all of the laboratory work of third-year chemistry students, and bringing together all of the traditional subdisciplines of chemistry (analytical, inorganic, organic and physical chemistry).[35] The course includes one recently developed discipline-specific, and nine "interdisciplinary" experiments. These experiments either combine approaches from two or more of the subdisciplines (see ref 35 for examples) or that represent experimental work that is uncommon in traditional laboratory courses, for example that relating to materials science (e.g., ref 36). The course is team-taught; at least one faculty member from each traditional subdiscipline is involved. Course-level learning objectives are provided in the Supporting Information of ref 35; the course was not designed specifically to prepare students for research.

We use "experiment" to refer to a coherent set of laboratory tasks taking either one (in most cases), two or three blocks of 4 h in the laboratory to complete, along with pre- and postlab tasks. Over the time period of this study, the course offered ten analytical, nine inorganic, 23 organic and 14 physical chemistry experiments, and nine interdisciplinary or novel experiments, with some variation from year-to-year. A list of the experiment titles is provided in Table S1 of the Supporting Information. Out of a total of 65 experiments offered, students complete either 18 or 36 experiments over two semesters depending upon their degree program.[35] This course provides an excellent context within which to consider chemistry laboratory instruction, because it encompasses experiments representative of four traditional subdisciplines, and because of the variation in instructional style of the experiments. Many of the experiments offered could be considered to be typical, in that they are similar to those commonly present in many bespoke and commercially published laboratory curricula (for example: Ro-vibrational spectroscopy of HCl; Determination of quinine by fluorescence and absorbance; Bromination of *trans*-cinnamic acid; Preparation and magnetism of chromium(III) acetate). Delivery of the experiments is also typical, for example students are generally required to complete prelaboratory work including safety assessments, to complete the laboratory activities alone or with a laboratory partner, and then to submit a postlaboratory report. A few experiments are, however, less typical. For example, several of the organic chemistry experiments were redesigned to capture problem-solving approaches, and one is a "dry" laboratory which addresses the use of literature and databases relevant to synthetic chemistry. Several recently developed interdisciplinary or novel experiments incorporate inquiry-based learning approaches.

A further feature of the redesigned course is that students determine their own curriculum by selecting a suite of experiments to complete (within limits: minima apply for each of the four subdisciplines of chemistry). As a result nearly all students finish the course with a laboratory curriculum that differs from their peers.[35] Over a five-year period, the breakdown of student-selected experiments by type was 19% analytical, 25% inorganic, 26% organic, 21% physical, and 10% interdisciplinary or novel.[35] The single most subscribed experiment accounted for 4.5% of all of those undertaken.

■ CTERS IN CHEMISTRY: IS WIEMAN'S INVENTORY APPLICABLE?

To consider the extent to which chemistry laboratory experiences provide opportunities to practice cognitive tasks associated with experimental research, it is first necessary to establish the appropriate inventory of tasks. Here "experimental research" refers to practical tabletop activities aimed at the systematic observation, understanding or control of the natural world. Breslow[37] proposes "Some chemists investigate the natural world and try to understand it, while other chemists create new substances and new ways to perform chemical changes that do not occur in nature" (p. 2). We take "experimental research" to incorporate both of these. To our knowledge no cognitive task analysis for the role of chemistry researcher has been published, nor has any CTA relevant for individual subdisciplines. There are however a number of sources of relevant information.

Wieman[28] identifies nine broad categories of CTERs that are likely to apply to all branches of science. The categories are 1. *Establishing research goal*; 2. *Defining criteria for suitable evidence*;

3. *Determining feasibility of experiment*; 4. *Experimental design*; 5. *Construction and testing of apparatus*; 6. *Analyzing data*; 7. *Evaluating results*; 8. *Analyzing implications if results are novel and/or unexpected and confirmed*; and 9. *Presenting the work* (see also Table 1). Wieman[28] reported that scientists from fields other than physics agree that his list of cognitive tasks "generally apply... although the specifics vary." (p. 349).

Comparison with other analyses of working scientifically corroborates this applicability: Fuhrman and co-workers[38,39] analyzed tasks in high school chemistry laboratories, inventorying 28 tasks. The Australian Education Council[40] listed 26 tasks undertaken when working scientifically and the list informed efforts to reform chemistry laboratories at the secondary and tertiary levels.[41] Only the tasks in their "*Acting responsibly*" category are absent from Wieman's inventory. The coauthor of a well-known chemistry textbook identified nine activities in which scientists must engage during research.[42] The American National Research Council[32] listed eight science practices that should be part of K-12 science education, which Cooper et al.[43] argued are also applicable undergraduate study. Wieman's list is in excellent alignment with each of these analyses.

However, not all assessments of the thinking a research chemist uses are so neatly aligned. To develop curriculum that is true to the practices of chemists, Sevian and Talanquer[44] articulated a framework for the progression of chemical thinking over time. They identified core practices of analysis, synthesis and transformation. They argue that teaching of chemistry should focus on activities of investigation, design and evaluation, which clearly fits Wieman's approach. Further, they enumerate core questions that drive chemical thinking (e.g., "*How do we identify chemical substances?*").[44] Similarly, LaFarge et al.[45] proposed an organic chemistry curriculum centered around the questions professional organic chemists answer (e.g., "*How can the structure of an organic species be determined?*"). While these provide helpful context, they do not consider *types* of student thinking in chemistry laboratories.

Given the excellent alignment of Wieman's inventory with the analyses described above, this work directly uses the nine broad categories and the 29 specific CTERs proposed by Wieman to consider laboratory experiences in all branches of chemistry. We did not make an addition relating to the Australian Education Council's "Acting responsibly" category[40] because this may be addressed in lecture courses rather than laboratories. Further, the authors' discussions with faculty members who teach or conduct research across the core subdisciplines in North America or Europe did not reveal any cognitive tasks necessary for experimental research in chemistry to be missing from Wieman's inventory. One potential exception is planning for safety, which might be worthy of a separate category given its importance in the chemical sciences. Thinking about safety could be interpreted as forming part of CTERs 1c, 3a, 4a, 4c, and 5a, so we have not explicitly added it as a CTER here. The closest incorporation of planning for safety is within the category of experimental design, in which Wieman's CTER 4c (Finalizing design) includes incorporating *performance requirements* when designing the experiment. Later, when planning for safety is a cognitive task required of students in specific experiments of the example course, we ascribe it to CTER 4c, although in a way that shows whether 4c occurs solely via thinking about safety or if other aspects of finalizing the experimental design are involved.

METHODS: APPLYING A CTER FRAMEWORK TO A CHEMISTRY LABORATORY CURRICULUM

We used Wieman's inventory of CTERs[28] as a framework for analyzing the curriculum of the example course. This provided data with which to consider the following questions: (1) How are CTERs distributed across our course curriculum, and what factors affect the presence/absence of CTERs in an experiment? (2) How much practice do students receive in each CTER? To what extent does the course offer the opportunity to prepare for research? (3) How can the results of a CTER analysis be used to inform course design?

Making use of Wieman's description of each cognitive task in his inventory,[28] we assessed the CTERs in each experiment, building a "map" of the cognitive activities in the course. Coding was binary: a "Yes" was recorded if students performing the experiment would be required to undertake some or all of the thinking in the given description, while "No" indicated that such thinking would not be required.

An initial assessment of the CTERs present was carried out by the faculty member responsible for each experiment as part of a general evaluation of the course. The teaching team prepared for this task by discussing how to interpret the CTERs. During our own later discussions the authors found three of the tasks more difficult to interpret than others: Task 2a (deciding what data would be convincing); 5g (collecting experimental data); and 8 (analyzing implications). These merit additional explanation of how the tasks have been interpreted. We provide this information in Table 2.

We examined the initial assessment results and identified where members of the teaching team may have understood the CTERs in different ways. One author, starting with the initial assessments and mindful of potential areas of inconsistency, examined in detail the instructions provided in the laboratory manual (written by course instructors for student use) to validate the analysis. The manual was close-read to determine which instructions (if any) required students to engage in any of the CTERs, thus establishing which CTERs formed part of each experiment. In some cases, the set of CTERs observed was surprising for its absences (for example many synthetic chemistry experiments included no instructions relating to chemically characterizing a reaction product). In such extreme cases, the actual practices of students were verified by a combination of examining samples of student laboratory reports, and/or discussion with the faculty member or graduate student teaching assistants responsible for the experiment's delivery. This revealed that individual experiments in the laboratory manual often omitted instructions that applied broadly (across multiple experiments); those instructions appeared to form part of the course culture that students understood. As long as the thinking was clearly required of all students performing the experiment, CTERs arising this way were coded "Yes".

We were interested in whether an experiment has the student performing *any* portion of the thinking described in the CTER. CTER 1a, for example, has three possible criteria (deciding if research goal is interesting *or* worthwhile *or* timely); if a student thought only about their level of interest in the experiment, we still recorded the CTER formed part of it. Further, the depth of student thinking was deemed irrelevant; we evaluated whether the experiment offered the opportunity to practice these tasks rather than whether students achieve any particular level of performance.

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Table 2. Interpretation Notes for Three Cognitive Tasks for Which the Assessment of the Presence or Absence of the Task Was Challenging[a]

CTER	Interpretation Notes
2a, deciding what data would be convincing given the state of the field	An assessment that this task was present was typically triggered by one of two cases: (a) In synthesis-based experiments, a requirement for students to interpret spectroscopic (e.g., IR, NMR) or other characterization (e.g., GC) data in an open-ended way to conclude whether or not the desired product was made. Often this involved students observing and interpreting features within characterization data but rarely involved them deciding on which characterization method to use, presumably because efficient operation of teaching laboratories means only limited methods are available. (b) In physical or analytical experiments, either a requirement for students to decide how much data to collect, or to decide whether their collected data were of a high enough quality to allow conclusions to be drawn.
5g, collecting experimental data	Task 5g is in the category "construction and testing of apparatus". In the CTER assessments presented here for synthetic chemistry work, we consider collection of experimental data to have taken place provided that some form of product characterization has been carried out, regardless of whether the characterization is sophisticated (e.g., spectroscopic) or simple (e.g., melting point, visual description). If product characterization is not undertaken then this task was judged to be absent. In other words, the synthesis of a chemical is not data.
8, analyzing implications if results are novel and/or unexpected and confirmed	Interpreted strictly, this task is unlikely to exist in a teaching laboratory environment due to the requirement of novelty; even if students are engaged in experiments that require them to define their own research question, such as those described in literature as having a high-degree of inquiry,[15] the results are unlikely to be truly novel. Accordingly, in assessing this CTER we chose to focus on the requirement to analyze implications. Experiments in which students must describe the meaning of their results or contemplate what their results tell them were assessed to involve this task.

[a] Descriptions of the tasks are paraphrased from ref 28.

We deemed a cognitive task to be required if it came up in any part of the experiment, including: prelaboratory assignments; in-laboratory work; or postlaboratory assignments. There were instances of a particular cognitive task appearing to be required, but for which the laboratory manual was so prescriptive as to minimize student engagement in the task. For example, in the laboratory manual the experiment's background material might discuss various variables relevant to a measurement, but then prescribe which variable students must measure. In such cases we assessed that the students were not required to engage in deciding which variables need to be considered (CTER 2b). We assumed students execute the experiment as laid out in the manual, and we did not account for engagement with cognitive tasks occurring during unplanned problem-solving, such as 3b (Analyze contingency options) and 7a (Checking the results, when they come out differently than expected). However, if "straightforward" progress through the experiment still resulted in students performing CTER 7a, then it was included. Voluntary engagement with cognitive tasks additional to those required in the experiment, perhaps while a student follows their personal curiosity and dives deeper into a topic, were not counted.

Subjectivity exists in the assessment of CTERs present; assessors bring their experiences of teaching chemistry and potentially familiarity with the experiments. Additionally, distinction between CTERs is not always straightforward in practice. For example, where is the line between preliminary and final experimental design? While we have attempted to address ambiguity in each task, we do not intend to objectively characterize laboratory curriculum. Instead, the utility of CTER-based analysis lies in its ability to structure and promote reflection and to inform decisions about curriculum design. We recommend that when examining the CTERs present in a laboratory course or curriculum, both those involved in teaching the experiments and those who will use the output of the examination to make decisions should be involved in assessing the CTERs.

In the Results and Discussion section below, we present the outcomes of applying this framework to the example course.

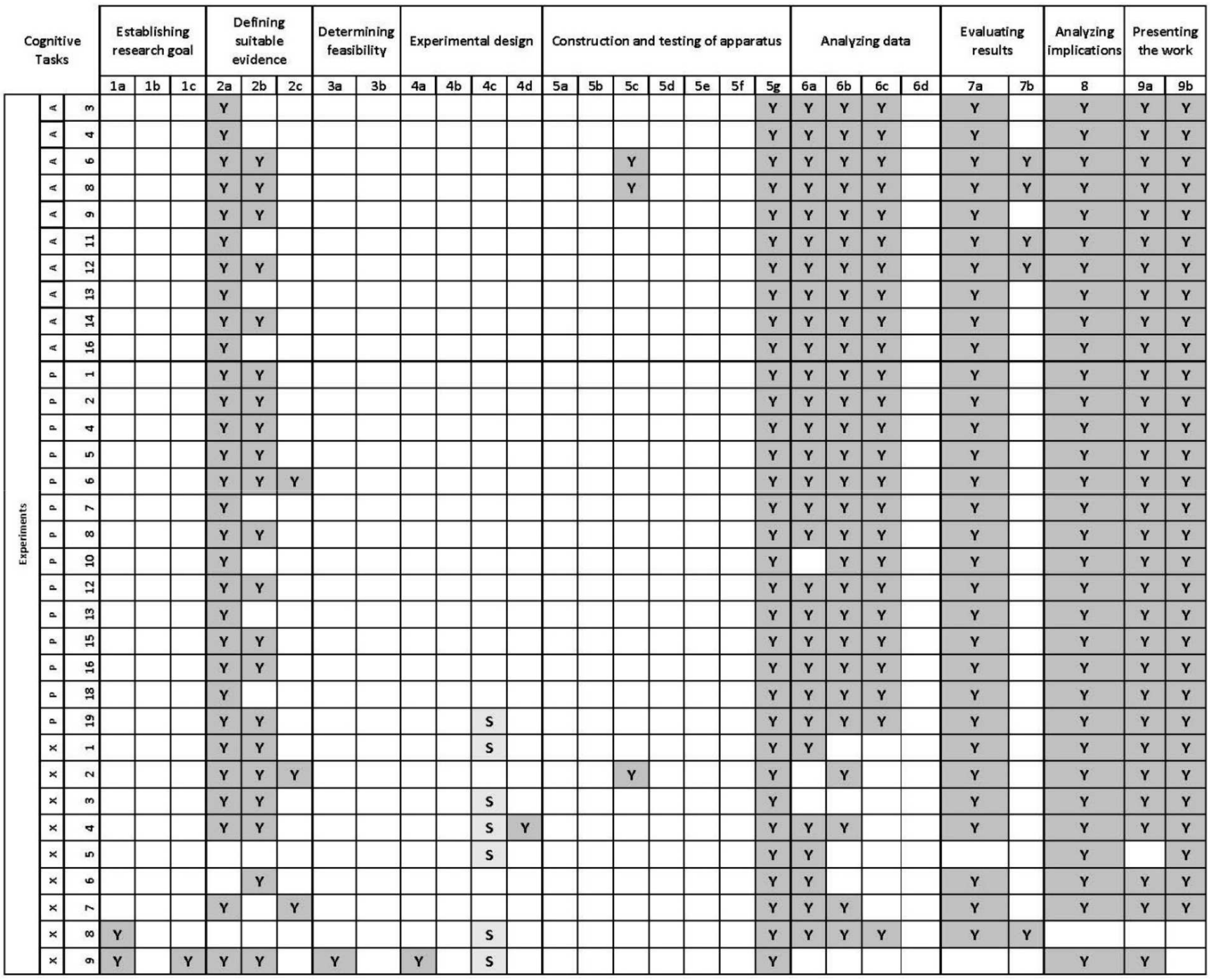
■ RESULTS AND DISCUSSION

The questions in the Methods section will now be answered for the laboratory course presented in the Context section. This provides an illustrative example of how various CTERs may be experienced by students across various types of laboratory experiments.

Characterizing Laboratory Experiments in Terms of Their CTERs

Figures 1 and 2 show the CTERs assessed as required by each experiment in this course, where Figure 1 reports on analytical (A), physical (P), and interdisciplinary or novel (X) experiments and Figure 2 lists inorganic (I) and organic (O) experiments. Of the nine categories of CTERs identified by Wieman,[28] all are represented at least once across the 65 experiments, although some feature much more often than others. Of the 28 CTERs, we have identified 20 present in the curriculum of this laboratory course. On average, an individual experiment presents students with about seven CTERs; however, significant variation is present, with the highest number in one experiment being 12, and the lowest zero.

We note both similarities and differences between the CTERs considered to be present in introductory physics laboratory



Cognitive Tasks			Establishing research goal			Defining suitable evidence			Determining feasibility		Experimental design				Construction and testing of apparatus							Analyzing data				Evaluating results		Analyzing implications	Presenting the work	
			1a	1b	1c	2a	2b	2c	3a	3b	4a	4b	4c	4d	5a	5b	5c	5d	5e	5f	5g	6a	6b	6c	6d	7a	7b	8	9a	9b
Experiments	A	3				Y															Y	Y	Y	Y		Y		Y	Y	Y
	A	4				Y															Y	Y	Y	Y		Y		Y	Y	Y
	A	6				Y	Y										Y				Y	Y	Y	Y		Y	Y	Y	Y	Y
	A	8				Y	Y										Y				Y	Y	Y	Y		Y	Y	Y	Y	Y
	A	9				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	A	11				Y															Y	Y	Y	Y		Y	Y	Y	Y	Y
	A	12				Y	Y														Y	Y	Y	Y		Y	Y	Y	Y	Y
	A	13				Y															Y	Y	Y	Y		Y		Y	Y	Y
	A	14				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	A	16				Y															Y	Y	Y	Y		Y		Y	Y	Y
	P	1				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	2				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	4				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	5				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	6				Y	Y	Y													Y	Y	Y	Y		Y		Y	Y	Y
	P	7				Y															Y	Y	Y	Y		Y		Y	Y	Y
	P	8				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	10				Y															Y		Y	Y		Y		Y	Y	Y
	P	12				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	13				Y															Y	Y	Y	Y		Y		Y	Y	Y
	P	15				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	16				Y	Y														Y	Y	Y	Y		Y		Y	Y	Y
	P	18				Y															Y	Y	Y	Y		Y		Y	Y	Y
	P	19				Y	Y						S								Y	Y	Y	Y		Y		Y	Y	Y
	X	1				Y	Y						S								Y	Y				Y		Y	Y	Y
	X	2				Y	Y	Y									Y				Y		Y			Y		Y	Y	Y
	X	3				Y	Y						S								Y					Y		Y	Y	Y
	X	4				Y	Y						S	Y							Y	Y	Y			Y		Y	Y	Y
	X	5											S								Y	Y						Y		Y
	X	6					Y														Y	Y				Y		Y	Y	Y
	X	7				Y		Y													Y	Y	Y			Y		Y	Y	Y
	X	8	Y										S								Y	Y	Y	Y		Y	Y			
	X	9	Y		Y	Y	Y		Y		Y		S								Y							Y	Y	

Figure 1. Map of CTERs assessed to be present in (marked "Y") or absent from (blank) analytical, physical, and interdisciplinary/novel experiments of the example laboratory course. If CTER 4c is present solely due to an aspect of planning for safety, the marking "S" is shown. Experiment codes at left begin with A for analytical chemistry experiments, P for physical, and X for interdisciplinary or novel experiments.

courses and those assessed as present here. Wieman argued[28] that such physics courses typically only include 6c and parts of 4d, 7a, and 9a, although it seems that 5g (Collecting experimental data) ought to occur as well. The example chemistry laboratory course offers a greater number of CTERs than the introductory physics course; this may be related to a stronger emphasis on preparation for research in the higher year-level chemistry course or simply to differences in content presentation.

We judged four CTERs to be close to ubiquitous in our investigation. Tasks 2a, 5g, 8, and 9a are present in >85% of experiments, while six others were assessed as appearing regularly (2b, 6a−c, 7a, and 9b are present in ∼40−85% of experiments). If planning for safety is included in CTER 4c, it too becomes regularly required. The remaining 18 CTERs are present in less than 10% of the experiments, with eight not present at all. Of these 18 CTERs, those related to establishing research goals (task category 1), determining feasibility (category 3), experimental design (category 4), and construction and testing of apparatus (category 5) are notably absent or rare.

Figure 3 explores the results of mapping the CTERs in the course; it shows the percentage of experiments of each type (A, I, O, P, or X) that include at least one CTER from each of the nine categories. The CTER categories of defining criteria for suitable evidence (category 2), construction and testing apparatus (category 5), analyzing implications (category 8), and presenting the work (category 9) are present in a large fraction of the experiments, regardless of the type. Conversely, cognitive tasks related to establishing research goals (category 1), determining feasibility (category 3), and experimental design (category 4) are absent for most types of experiment and rare in the remainder. CTERs in categories 6 (Analyzing data) and 7 (Evaluating results) are in a high proportion of experiments in some subdisciplines and a low proportion of others. If planning for safety is judged to form part of category 4 (as CTER 4c), then the prevalence of category 4 also shows significant variation between subdisciplines.

To compare variations in student experience of CTERs between the different types of experiment, Figure 4 shows the proportion of individual CTERs from each of the nine categories present. For a given category of CTER and type of experiment, a proportion of 1.0 indicates that all experiments of that type included all of the individual CTERs in that category. For example, analytical chemistry experiments include on average approximately half the possible CTERs in category 2, and so the proportion is 0.5. Student engagement with CTERs related to establishing research goals (category 1) is almost nonexistent;

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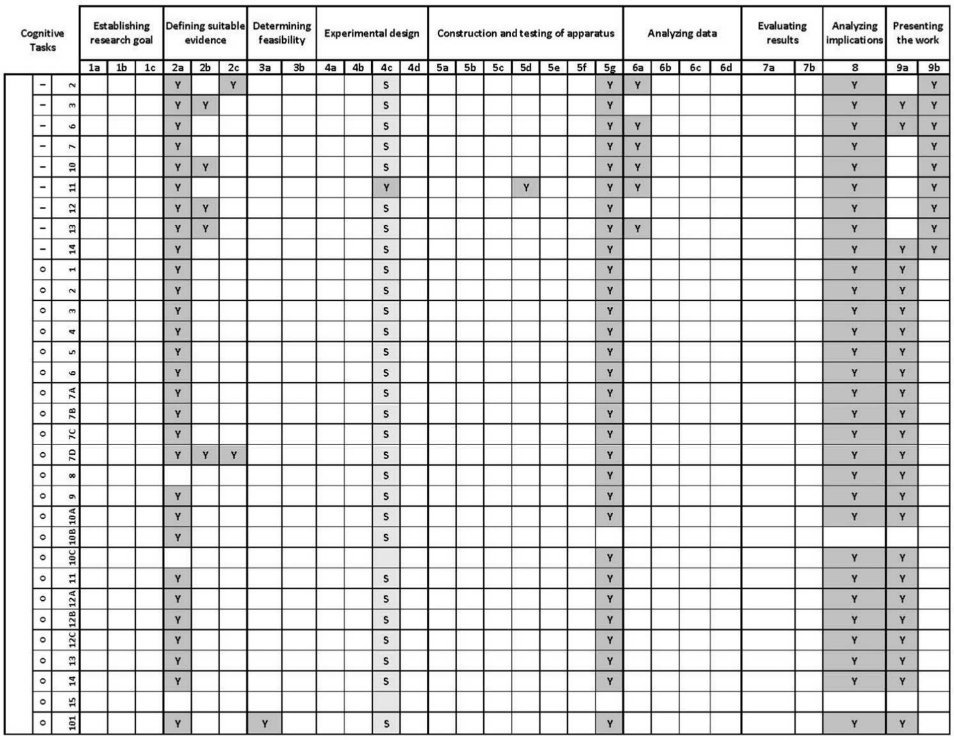


Cognitive Tasks		Establishing research goal			Defining suitable evidence			Determining feasibility		Experimental design				Construction and testing of apparatus							Analyzing data				Evaluating results		Analyzing implications	Presenting the work	
		1a	1b	1c	2a	2b	2c	3a	3b	4a	4b	4c	4d	5a	5b	5c	5d	5e	5f	5g	6a	6b	6c	6d	7a	7b	8	9a	9b
I	2				Y		Y					S								Y	Y						Y		Y
I	3				Y	Y						S								Y							Y	Y	Y
I	6				Y							S								Y	Y						Y	Y	Y
I	7				Y							S								Y	Y						Y		Y
I	10				Y	Y						S								Y	Y						Y		Y
I	11				Y							Y					Y			Y	Y						Y		Y
I	12				Y	Y						S								Y							Y		Y
I	13				Y	Y						S								Y	Y						Y		Y
I	14				Y							S								Y							Y	Y	Y
O	1				Y							S								Y							Y	Y	
O	2				Y							S								Y							Y	Y	
O	3				Y							S								Y							Y	Y	
O	4				Y							S								Y							Y	Y	
O	5				Y							S								Y							Y	Y	
O	6				Y							S								Y							Y	Y	
O	7A				Y							S								Y							Y	Y	
O	7B				Y							S								Y							Y	Y	
O	7C				Y							S								Y							Y	Y	
O	7D				Y	Y	Y					S								Y							Y	Y	
O	8											S								Y							Y	Y	
O	9				Y							S								Y							Y	Y	
O	10A				Y							S								Y							Y	Y	
O	10B				Y							S																	
O	10C																			Y							Y	Y	
O	11				Y							S								Y							Y	Y	
O	12A				Y							S								Y							Y	Y	
O	12B				Y							S								Y							Y	Y	
O	12C				Y							S								Y							Y	Y	
O	13				Y							S								Y							Y	Y	
O	14				Y							S								Y							Y	Y	
O	15																												
O	101				Y			Y				S								Y							Y	Y	

Figure 2. Map of CTERs assessed to be present in (marked "Y") or absent from (blank) inorganic and organic chemistry experiments of the example laboratory course. If CTER 4c is present solely due to an aspect of planning for safety, the marking "S" is shown. Experiment codes at left begin with I for inorganic, and O for organic experiments.

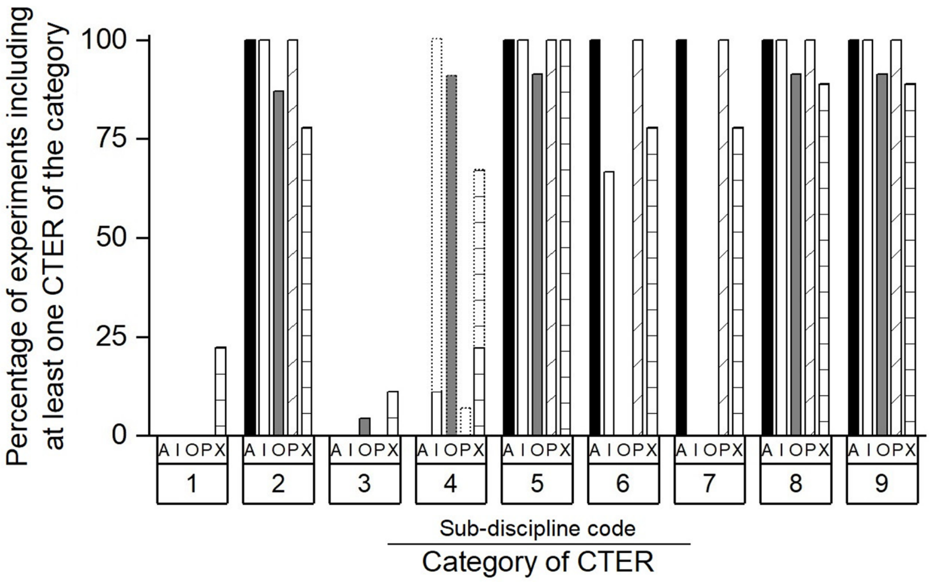
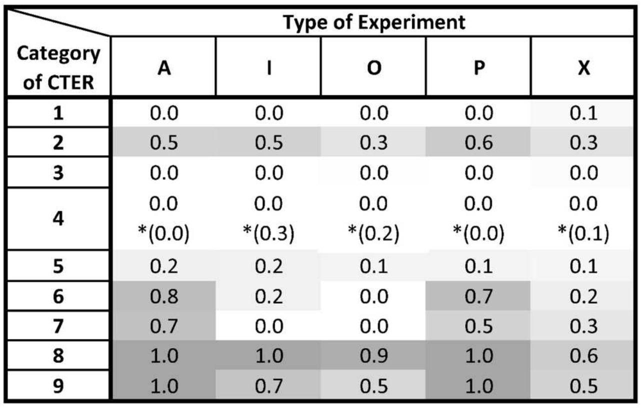


Figure 3. Proportion of experiments of each of type which involve one or more CTERs from each of the nine broad categories. Category numbers are defined in Table 1. A, I, O, P, and X represent the types of chemistry experiments in the course: Analytical, inorganic, organic, physical, and interdisciplinary or novel, respectively (shown as black, white, gray, white with diagonal lines, white with horizontal bars, respectively). For category 4, the additional impact of including planning for safety in CTER 4c is shown with dotted outline.

only interdisciplinary/novel experiments show a nonzero proportion. The CTERs of category 2 are modestly represented, but some variation between subdisciplines is observed. Students are not required to think about tasks in categories 3 and 4 at all, with the exception of when planning for safety is incorporated into category 4, but even then the proportions are low. Students meet CTERs of category 5 about equally across subdisciplines. Strong variation between subdisciplines is seen for the CTERs in categories 6 and 7; analytical and physical chemistry experiments usually require most of the CTERs in these categories while inorganic and especially organic chemistry experiments do not. Interdisciplinary/novel experiments are intermediate between the two extremes. Students engage with almost every CTER in category 8 in almost every experiment, but interestingly interdisciplinary/novel experiments show the lowest proportion. Category 9 has high proportions for



Category of CTER	Type of Experiment A	I	O	P	X
1	0.0	0.0	0.0	0.0	0.1
2	0.5	0.5	0.3	0.6	0.3
3	0.0	0.0	0.0	0.0	0.0
4	0.0 *(0.0)	0.0 *(0.3)	0.0 *(0.2)	0.0 *(0.0)	0.0 *(0.1)
5	0.2	0.2	0.1	0.1	0.1
6	0.8	0.2	0.0	0.7	0.2
7	0.7	0.0	0.0	0.5	0.3
8	1.0	1.0	0.9	1.0	0.6
9	1.0	0.7	0.5	1.0	0.5

Figure 4. Proportion of the specific CTERs from each of the nine broad categories present in the experiments of each type. Category numbers are defined in Table 1. A, I, O, P, and X represent the types of chemistry experiments in the course: Analytical, inorganic, organic, physical, and interdisciplinary or novel, respectively. For a given category of CTER and type of experiment, a proportion of 1.0 would indicate that all experiments of that type included all the individual CTERs in that category. For example, analytical chemistry experiments include on average approximately half the possible CTERs in category 2, and so the proportion "0.5" is shown. Values rounded to closest 0.1. Values for category 4 are shown without and *(with) planning for safety included in CTER 4c.

analytical and physical chemistry and modest values for organic and interdisciplinary/novel experiments; the proportion for the inorganic subdiscipline is in-between.

Understanding Variations in CTER Prevalence between Subdisciplines. Our analysis showed that CTERs in categories 6, 7, and 9 are less often required in inorganic and organic chemistry experiments than for physical and analytical chemistry, or for the interdisciplinary or novel experiments. We wondered if this finding was specific to the course examined or more general in nature.

It has been reported that instructors of organic chemistry laboratories may emphasize student learning of techniques more than instructors in other subdisciplines,[5,6] and Mohrig claimed that question- or problem-driven approaches are rare in organic laboratory courses.[46] To investigate whether the quantity of CTERs present for organic chemistry in the course was representative of similar courses, we collected laboratory manuals for organic chemistry laboratory courses at the equivalent year-level from a large, public, research-intensive university in North America, a midsized university in the United Kingdom, and a polytechnic university in Denmark. We assessed the CTERs that a student would experience in each experiment of those courses. Table 3 gives an overview of the CTERs that were commonly coded as present and shows that the courses are broadly similar in terms of the CTERs captured. Although not comprehensive, the data suggest that the example course's organic chemistry curriculum is not an aberration in its breadth of CTERs. However, our work showed some organic chemistry experiments from other institutions captured CTERs that our course does not (4b, 6a, and 9b: Analyzing relevant variables, Modeling the data, and Explaining the work). Interestingly, in some cases we found experiments at other institutions that were identical in synthetic approach and target, but differed in their set of CTERs. For example, an experiment in this course dealing with the synthesis of *N*,*N*-diethyl-*m*-toluamide does not require students to perform CTER 4b (Analyzing relevant variables that may lead to systematic errors), while the same experiment at one of the other institutions does. The difference originates in the lab manuals: one begins with a series of questions for students to think about, including why the glassware must be dry, and why a stoichiometric excess of reagent is required in a particular step. In answering these prompts, students engage in CTER 4b.

Table 3. Summary of CTERs Commonly Assessed as Present in Example Organic Chemistry Laboratories[a]

Course and Institution Description	Number of Experiments Assessed	Common CTERs
This course (organic chemistry portion)	23	2a, 5g, 8, 9a
Two organic chemistry courses at third-year level at a large, public North American university	13	2a, 5g, **6a**, 8, 9a, **9b**
Organic chemistry course at second-year level at midsize UK university	8	2a, 5g, 8, 9a
Organic chemistry laboratory course at second-year level at a Danish polytechnic university	26	2a, **4b**, 5g, 8, 9a

[a] A cognitive task was deemed common if it appeared in at least 20% of the assessed experiments. Boldfaced cognitive tasks are uncommon in the upper-level organic chemistry experiments in this course. Courses examined at the European institutions are second-year level, while the North American courses are third-year level, to account for the UK and Denmark having an additional year of schooling before university admission compared with North America. The 13 experiments at the North American university span 17 laboratory periods, while each experiment at the other institutions corresponds to one period.

Understanding Variations in CTER Prevalence in "Less Traditional" Experiments. The example course includes one discipline-specific, and nine interdisciplinary or novel experiments, all of which were recently developed. These experiments involve several CTERs that are either rarely required or absent from the more traditional experiments, as shown in Table 4. While these new experiments bring CTER breadth into the course, they do not contribute substantially to student practice of these CTERs since they represent only a small fraction of the total experiments in the course and students do not undertake all the experiments available.

Table 4. CTERs That Are Present Uniquely (*) or That Are Rarely Found Outside the More Recently Developed Experiments of the Course[a]

CTERs Found Mostly in the Recently Developed Experiments	Number of Recently Developed Experiments Incorporating the CTER	Total Number of Course Experiments Incorporating the CTER
*1a (Deciding value of goal)	2	2
*1c (Evaluating constraints on research goal)	1	1
*3a (Predicting feasibility of experiment)	2	2
*4a (Exploring preliminary experimental design)	1	1
*4d (Developing data acquisition strategy)	1	1
5c (Collecting data on components or apparatus)	1	3
7b (Testing the data)	1	5

[a] CTER descriptions are brief; consult Table 1 for full description.

Although the number of recently developed experiments is small, the extent of extra CTERs present is noteworthy. These experiments do not represent a new subdiscipline of chemistry and the extra CTERs do not arise from the nature of the chemistry. Therefore, their presence suggests that there was either a change in the learning goals faculty have for laboratories or that a different pedagogical approach was employed when developing these experiments. All of them were designed after the decision to unite the four subdisciplines was made, meaning faculty desire to integrate the subdisciplines experimentally may have been a factor. Faculty members involved did not have formal instruction in laboratory pedagogies when hired, but all worked with science education specialists to align teaching and learning with findings from educational research. In part, this involved assessing the state of the laboratory course by examining which major topics were involved in each experiment and the initial assessment of their CTERs. Furthermore, the faculty and specialists articulated course-level learning outcomes. It is likely that these acts of reflection on the course are responsible for the change in pedagogy seen. However, we cannot conclude that awareness of the concept of CTERs itself was a dominant factor, as about one-third of the new experiments were developed before initial CTER assessment.

Figures 1, 2, and 3 show the interdisciplinary or novel experiments (denoted by "X") require the broadest range of CTER categories, and represent the only type of experiment that includes any CTERs from category 1 (establishing research goals), with two of the nine experiments requiring at least one of these CTERs. How do these experiments incorporate this CTER category, given that it is rare for typical experiments? For these two experiments the instructions are less prescriptive and involve increased student decision-making as part of the experimental procedure. This can be expressed as a move away from expository-style experiments to an inquiry or problem-based style.[47] One interdisciplinary/novel experiment (X-9) was deliberately designed to incorporate aspects of inquiry.

Characterizing the Course as Preparation for Experimental Research

To what extent does this course offers opportunities for students to prepare for research, and how does this align with course goals and the degree program as a whole? While considering which CTERs are present in *individual experiments* lends insight into specific learning events and allowed us to compare groups of experiments, it does not characterize the breadth or depth of how our course as a whole prepares students for research because of the atypical course organization.[35] Here, we illustrate the analysis that could provide an instructional team with data to inform whether a course meets intended outcomes, and opportunities for further development.

In our example course, students select 18 or 36 individual experiments to complete over two semesters (see ref 35). For the analysis below, we consider only the subset of students who undertook 36 experiments. These were chemistry major or honors degree program students. The course has no restrictions on the order in which experiments are completed. We collected records of which experiments students completed and their grades over a five-year period from fall 2012 to spring 2017. Only data from students who successfully completed both semesters of this course in the five-year period were analyzed. If a student did not pass an experiment, we assumed the student had not engaged in the associated CTERs. After expunging records of failed experiments, the data set encompassed 9,903 experiments undertaken by 283 students. This data set was combined with the results of the assessments of the CTERs involved in each individual experiment (Figures 1 and 2) to determine which CTERs each student experienced, and how many times. We counted tasks in two ways:

1. To determine *breadth of experience,* we determined whether a task was met at least once within the set of experiments a student completed.

2. To determine *depth of experience*, we determined the total number of times each CTER appeared in a student's records. For example, if a student completed 36 experiments and each experiment included task 9a, then 36 instances were recorded.

We counted CTER on a per-lab period basis; if a single experiment spanned two periods, we assumed students experienced each of the experiment's CTER twice. This was a necessary simplification and students may have had extended experience with each task or experienced a subset of the tasks in each period.

We examined records for the five-year period to determine the breadth of student experiences of each CTER. Only one student met all 20 of the CTERs present in the course. Despite only six CTERs being present in at least half the experiments, all students met at least 13 of the 20 CTERs present course-wide by the end of their 36 lab periods. Twenty-two percent of students met 13 CTERs, while sixty-seven percent of students met between 15 and 17 CTERs during the course.

It is optimistic to think that a single experience with a cognitive task is sufficient for meaningful progress toward mastery of the task. Proverbially,[48] and supported by extensive study (e.g., refs 49, 50), repetition is known to be important for learning. We therefore also considered the depth of student experience. The number of times students experienced a CTER varied from 0 to about 35, where a value of 36 would indicate that the cognitive task was experienced in every experiment that a student completed. The "average" student encountered each of the following CTERs at least 14 times: 2a, 2b, 4c (if safety included), 5g, 6a, 6b, 6c, 7a, 8, 9a, and 9b. Assuming a CTER is only engaged in once per lab period, the "average" student met a cognitive task requirement on a total of 251 occasions (standard deviation 18).

Whether this course offers sufficient opportunities to prepare for research will always be subjective, but these results serve as a benchmark for CTER mapping of other courses. However, the CTER map of a laboratory course should not be considered in isolation; consider also the opportunities to engage in CTERs in other courses. Indeed, the application of the CTER approach could be extended to each student's entire chemistry laboratory experience, or even include nonlaboratory courses. A brief assessment of CTERs in other lab courses required in our chemistry degree programs showed that categories 1, 3, 4, and 5, which are poorly represented in the upper-level laboratory course are better-represented (though still atypical) in earlier courses, while the fraction of experiments that include tasks 6, 7, 8, and 9 increases from year one through year two to this upper-level course. Fourth-year undergraduates in our department typically join a research group to conduct a semi-independent research project over a period of several months; CTERs experienced there were not examined.

IMPLICATIONS FOR PRACTICE

The output of our CTER assessment provides rich data to support reflection by those involved in teaching lab courses or those engaging in curriculum renewal and design. Ways this data was used in our context or may be used by other educators include:

a. To understand the course, and student experience of it, from a cognitive tasks perspective. This included assessing how our course offers preparation for research including the presence, distribution, and frequency of individual CTERs. In doing so:

- Faculty involved in the course observed that students would practice a broader range of research skills if offered more opportunities to practice establishing research goals, determining feasibility, or undertaking experimental design. Of these, recent faculty development of the course has focused on incorporating experimental design. In the Supporting Information we describe strategies for adapting experiments to involve a greater number of CTERs.
- We drew attention to the fact that small changes in lab manual text can cause students to engage in additional expert-like thinking. In response, some faculty involved revised the lab manual or pre/post-lab activities to give students more opportunity to practice rare CTERs.
- We highlighted that students frequently engaged with some CTERs. For example, CTERs related to reporting the work were very common and thus frequently met by students. Some faculty decided the requirement to report the work after every experiment was superfluous and opted to reduce the number of lab reports or presentations required. Faculty hoped to address the common student concern of high course workload and aimed to allow students time to deeply engage in other CTERs.

b. To understand how differences in instructional design manifest in the student experience. For example, we observed that experiments designed to be inquiry-based appeared to involve more CTERs. Some of the course faculty continue to develop inquiry-based experiments while others have chosen to incorporate aspects of inquiry into existing experiments.

c. To inform how the course fits with others in the program in terms of exposure to CTERs; for example as part of a departmental curriculum review. A CTER analysis can be completed for each year of an overall program to explore whether it offers appropriate exposure to each CTER. While this has only been done informally in our department, two faculty have incorporated the idea of CTERs into scaffolding activities for students planning experimental work in a fourth year laboratory course.

d. To compare this course with those offered at other institutions. We hope others will employ this approach and make "big-picture" comparisons to ours so that we all may better understand chemistry laboratory curriculum. When institutions share similar experiments, it is interesting to compare if the same CTERs are involved, and if not, to decide if the local iteration is preferred. To assist comparison, the Supporting Information interprets Wieman's CTERs within the chemistry teaching lab context and describes how specific experiments of this course require students to engage in the CTERs.

e. As evidence for internal or external reviewers that students are meeting course or program outcomes, in particular for outcomes that may be hard to observe directly or which are not represented in typical assessments (e.g., lab reports).

SUMMARY AND AREAS FOR FURTHER STUDY

Considering alignment of laboratory instruction with the cognitive tasks engaged in by experimental researchers provides a viewpoint that is complementary to existing frameworks for evaluating laboratory teaching (e.g., hours of instruction, level of inquiry, modes of assessment, variety of hands-on training, extent of integration between subdisciplines, etc.). Applying this framework illustrated the ways chemistry laboratory experiments provide practice in CTERs and the ways that careful instructional design can impact student experience.

As in traditional physics laboratories,[29] requirements for students to determine experiment feasibility or to design experiments are rare in traditional chemistry laboratory experiments. Tasks related to defining criteria for suitable evidence, analyzing implications, and presenting the work were frequently required regardless of subdiscipline. General differences across subdisciplines were identified in our analysis; however, these seem likely to be the result of differences in experiment design and/or in the emphasis placed on teaching techniques.

We described ways the outcome of this approach could inform laboratory curricula and pedagogy. Specifically, we addressed rethinking course learning goals in terms of cognitive tasks, and showed how simple changes in instructional design may allow the capture of additional CTERs. We also addressed how this approach benefits discussions of program-level outcomes or design and the field of chemical education as a whole.

A remaining point of interest is the level of students' performance of CTERs; we focused exclusively on opportunities for practice and cannot make claims about student progress in mastering CTERs. In other words, does the collection of experiments in our course represent sufficient training for the students who go onto research? Would students be best served by meeting CTERs in *each* subdiscipline, or is it sufficient for students to practice experimental design, for example, only in physical chemistry contexts? Answering these will require detailed study of student research performance after graduation. Finally, study of student perceptions of the importance and accessibility of CTERs in chemistry laboratory experiments may provide useful insight for design of student experience and how research skills are framed in the chemistry curriculum.

ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00948.

List of experiments offered in the course; examples of how CTERs occur in chemistry teaching laboratory context, strategies and relative difficulty of adapting experiments to involve more CTERs (PDF) (DOCX)

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Notes

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