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Peer Instruction in the General Chemistry Laboratory: Assessment of Student Learning

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It is generally accepted that laboratory work is an integral part of an undergraduate education in chemistry. Many recent attempts to reinvigorate the lab course, especially at the general chemistry level, have the general aim of promoting a more active approach by the students. There is much interest in changing the format of the lab, from an expository (cookbook) approach to a more inquiry-based format, in which the students are responsible for designing some aspect of the experiment *(1).* Others have emphasized the critical role of the teacher *(2).* It has also been suggested that organizing the students into small teams can lead to improved satisfaction with lab because of the increased communication that occurs *(3).*

One approach *(4),* which has been applied recently in an attempt to improve student learning and understanding, is Workshop Chemistry (the Peer-Led Teaching and Learning model). In this model, students work in small, somewhat collaborative groups, each group taught and facilitated by an advanced undergraduate, who has previously taken the course and performed well. In most implementations of this model, the session has centered on a worksheet of challenging problems in general or organic chemistry, to be discussed and solved; experimental work has been less central. As one of the founder institutions in the Workshop Chemistry project, the University of Pittsburgh has utilized this model in a general chemistry recitation setting since 1995. In 1998, we extended the model to a subset of the general chemistry laboratory sections.

In this paper, we describe the format of the Workshop Chemistry labs and compare them with the conventional labs in our general chemistry program. We also present an assessment of the types and extent of learning in the Workshop labs based on a detailed analysis of students' performance on end-of-term lab exams. Ours is the first systematic investigation of the effectiveness of a Workshop Chemistry approach to improving student learning in a laboratory setting.

The Laboratory Program

Each general chemistry course at the University of Pittsburgh includes 3 credits of lecture and 1 credit of lab; the weekly 3-h lab session is organized into sections containing 20–24 students. Most of the 12 or 13 lab experiments each term build on chemical concepts originally presented in lecture. The experiments are quite challenging in their treatment of chemical concepts: detailed instructions are provided but many experiments include a final "Challenge" section, in which students generate their own experimental approach based on methods and ideas developed in earlier parts of the lab session.

Although the chemistry lectures and labs are assigned the same course number and students in a given lab section generally have the same lecture professor, the lecture and lab are run independently. Course lecturers are not involved with the teaching of lab. Conventional lab sections are taught by a graduate student (TA). Starting with the Fall 1998 semester, a few lab sections each term have been run in a Workshop format, in which the graduate TA is replaced by a team of 3 or 4 undergraduate mentors (whom we term UTUs—undergraduates teaching undergraduates). The UTUs are the sole teachers for their sections: no faculty or graduate TA is present. The class size is unchanged but the students are split into groups, one for each UTU mentor. Group size rarely exceeds 8 students. In both the conventional and the UTU-run labs, students carry out the lab work in pairs and write individual lab reports.

The content of the experiments is identical for the conventional and the UTU-run labs. Over the course of the project, we have taken advantage of the better teacher-to-student ratio in the Workshop labs to change the way in which these lab sections are run. Changes to the pre-lab introduction, inclusion of structured student–UTU discussions at the lab bench, and an emphasis on a small set of specific learning or understanding skills have been found to be effective.

Pre-Lab Introduction

In conventional labs, the experiment is introduced by the TA in a 15–30 min lecture, which includes the background chemical concepts and relevant lab techniques. A more active approach is adopted in the Workshop sections, which hold each student responsible for preparing an answer to a previously assigned pre-lab question, and for presenting this information to the group. This initiates a discussion in which the students teach each other much of the necessary information, with the UTU assisting where necessary. The formal pre-lab sessions are often quite short, with discussion continuing at the lab bench.

Student–UTU Discussion ("ID Stops")

There is a tendency in conventional expository labs for students to carry out the lab instructions without due attention to the reason for following them. Likewise, students often perceive the deficiencies in their experimental data at the end of the lab session, when it is too late to repeat steps or to improve their lab technique. To avoid such problems, we identified two or three key points during the lab work for each experiment at which students needed to pause and consider an important aspect of the experiment before proceeding. To sensitize the students to this crucial reflection activity and to give them practice in carrying it out, a UTU engages a pair of the students in structured question and answer discussion at these points, which we call "ID Stops" (i.e., Instructor Discussion Stops). Both the students and UTUs are made aware in advance of the recommended stage in the experiment at which an ID Stop will occur, and are alerted to the purpose of the planned discussion.

Students receive credit for these activities: out of the total of 10 points awarded each week, 2 are given for the pre-lab work and 1 for performance in the ID Stops. Most students score the maximum.

Learning and Understanding Skills

Learning in lab can go well beyond increased understanding of chemical concepts and the acquisition of lab techniques. We feel it is important to train students more generally in aspects of the scientific method. We chose to focus on four separate higher-level thinking skills, which could be carried successfully to other science courses, once acquired.

Learning Skill I

An awareness of the *organizational structure* of an experiment, including the relationship between its goals, its procedure, and the chemistry concepts it utilizes. We wanted students to have a global picture of each experiment, rather than to memorize a set of unconnected procedural steps.

Learning Skill II

The ability to *assess the quality* of a measurement or observation, or a set of these, and to respond appropriately in order to achieve higher quality data in the next stage of the experiment. We wanted students to develop a critical, active approach to carrying out experiments and to recognize and respect the connection between procedures and outcomes.

Learning Skill III

The ability to *explain* a set of results or to *draw conclusions* from them, using relevant chemistry concepts. We wanted students to base each explanation and conclusion on logical reasoning and an understanding of chemical processes.

Learning Skill IV

The ability to *apply* lab skills and lab-tested knowledge to new problems and situations.

The first two skills are particularly important. They encompass the most important ways in which we wish the students to *think,* as they perform an experiment and analyze the results. They also provide a useful framework for effective *understanding* of the goals and procedures of the experiment. The four skills are required for success in basic research and, as such, are also relevant to the lab instructors in their own fields of endeavor. Finally, such skills are generally applicable to problem solving by science students and scientists. Thus they provide a framework for *learning* a new and intricate subject. They are clearly related to the higher-level skills identified in Bloom's taxonomy *(5).*

In addition to these skills, two other general skills were emphasized: *oral communication in lab,* and *writing skills,* as practiced in portions of the lab reports.

Evaluation of the Workshop Chemistry Lab Project: Methodology

Student learning in the lab course was assessed via a written exam at the end of term, which accounted for 10–15% of the entire lab grade. The exam consisted of 5 questions, most of which required essay-style answers.

Past student performance on comparable end-of-term exams has been monitored informally for many years by one of the course instructors (MFG) and generally found to be disappointing. In fact, this was a major impetus for the current project, including its focus on the various learning, understanding, and general communication skills discussed above.

Since the start of the UTU project, MFG has scanned some of the exam responses each term, in an effort to assess whether changes in the workshop format were associated with improvements in student performance. Because objective evaluation of the written exams proved difficult, however, it was decided that a formal assessment protocol was needed, in which exam papers from several lab sections would be scrambled, re-graded and coded for analysis by a separate investigator (CLM), without knowledge of the instructional format, and using a reliable and goal-specific coding scheme.

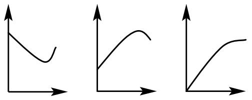
Because student registration for lab sections takes place each term without knowledge of the lab's instructional format, a systematic comparison of the student learning associated with each format may be thought of as a natural experiment, with random assignment to experimental (Workshop, run by UTUs) and control (conventional, run by a TA) conditions. To conduct a formal comparison, 15 of the 40 sections of Chemistry I lab offered during the Fall Term of 2000 were chosen for inclusion in a two-phase study. Phase I, the measurement development phase, focused on establishing a reliable and objective coding scheme for answers given on the final lab exam, using a portion of the total sample. The procedures developed in Phase I were then used to assess learning outcomes for the remainder of the sample (in Phase II). Only the Phase II results are presented here.

The Phase I data pool consisted of seven conventional (TA) sections, representing a total of 127 students, all of whom took one version of the lab exam. Three questions from that exam were chosen for analysis, because they focused mainly on the learning and understanding skills and less on aspects of chemistry likely to have been taught in lecture. Students' responses were analyzed to establish a set of rubrics and ranking schemes reflecting several of the learning, thinking, and general (written communication) skills described above. Ranking schemes were pretested until responses could be coded objectively and reliably by two observers (CLM and MFG) working independently. A final 3-point ranking system (1 = poor, 2 = fair, 3 = good) resulted, in which a *poor* ranking indicated omitted, incorrect, and unsatisfactory answers, and a *good* ranking included comprehensive as well as excellent answers.

The version of the final lab exam used in Phase II had similar goals and format to that used in Phase I. Table 1 lists the exam questions, A–C, which were selected for analysis, and the set of dependent measures derived from them. Two general measures, Clarity of Writing and Length of (Written) Response, were broken down by question, resulting in a total of 15 dependent measures. We adopted the following ranking scheme for scoring the Length of Written Response: 1 = 0–25% of a page filled; 2 = 26–50% of a page filled; and 3 = over 50% of a page filled. The empirical correlation between this purely numerical score and measures of answer quality was assessed as a separate step.

The sample for Phase II consisted of 6 control (conventional) sections, representing 109 students, and 2 experimental (Workshop) sections, representing 39 students. Each of the sections was taught by a different graduate TA or UTU team. Pooled exam papers were scrambled and coded, without knowledge of the student's identity, the lab instructor's identity, or the lab's instructional condition. The data were first compiled in Excel spreadsheets, then imported into SPSS (Version 11) for statistical analysis.

Table 1. Evaluative Questions for the Learning Outcome Phase

	Questions		Dependent Measures
A.	In Experiment 3, you determined the formula of hydrated (blue) copper sulfate (i.e., you found the value of x in $CuSO_4 \cdot x H_2O$), by adding water to initially anhydrous (white) copper sulfate. Describe in detail the step-by-step experimental procedure that you would adopt in order to obtain a high quality (i.e., an accurate) value of x. In your answer, state clearly what measurements and observations you would make and summarize how the data are analyzed to yield the value of x.	1. 2. 3.	Description of experimental procedures Awareness of factors needed for high quality results Description of data analysis
B.	How did you prepare for lab each week? Give a thoughtful account of the goals of preparing for lab and the procedures that you followed to achieve these goals. Please illustrate your answer by referring to one of the following experiments: 5 (Classes of Reactions), 7 (Limiting Reagent), or 10 (Electrical Conductance).	4. 5. 6.	Description of goals of preparing for lab Description of procedures of preparing for lab Application to specific experiment
C.	In Experiment 10, electrical conductances were measured while titrations were carried out. Consider the following pictures, which show typical conductance data. 	7.	Number of correct matches
	These represent (not necessarily in the correct order) the following reactions, with the second reagent being added in small quantities to the first reagent (i) H_2O (l) + Ca (s) (ii) NaOH (aq) + HCl (aq) (iii) CH_3COOH (aq) + NH_3 (aq)	8.	Accuracy of chemistry (identifying reaction products, phases)
	Match the reactions to the three pictures, giving your reasons. Explain clearly the observed changes in conductance, including balanced equations where relevant.	9.	Quality of logical interpretation of conductance data in terms of chemical reaction
	All questions: Clarity of writing and Length of (written) response were broken down by question, resulting in 3 Clarity of writing and 3 Length of (written) response indices.	10–12. 13–15.	Clarity of writing (A–C) Length of response (A–C)

Results

The primary results of the study are summarized in Tables 2–4. Table 2 shows that students in the experimental (Workshop) sections achieved a higher percentage of good (= 3) responses (32% across all quality measures, compared to 18% for the conventional labs), and a smaller percentage of poor (= 1) responses (34% across all quality measures compared to 50% for the conventional labs), and wrote longer answers (28% vs 12% who wrote responses filling over half a page). In fact, for nearly every measure of performance quality and written communication included in the study, participation in the Workshop labs tended to enhance students' learning relative to that indicated by test performance for students in the conventionally taught labs, with the differences often reaching statistical significance.

Specific Measures of Instructional Impact: Learning and Communication

The mean scores and standard deviations for each dependent measure are presented in Tables 3 and 4. The 15 means for the experimental and control sections were subjected to multivariate analysis of variance, which indicated that there was a highly significant ($p < 0.012$) overall effect of instructional format across the set of 15 measures. The tables present the t-values and probability levels, p, for each mean comparison, using adjusted t-values for the three measures characterized by unequal variances.[1] Judged individually, a value of $p < 0.05$ indicates that the group difference in the means is statistically significant (i.e., could have occurred by chance less than 5% of the time)—a result found for 9 of the 15 comparisons (60%), with one additional comparison

Table 2. Percentage of Lowest and Highest Ratings for each Dependent Measure[a] by Group

	Dependent Measures	Control Group (n = 109)		Experimental Group (n = 39)	
		Poor Rating (%)	Good Rating (%)	Poor Rating (%)	Good Rating (%)
	Question A				
1.	Description of experimental procedure	50	17	36	33
2.	Awareness of factors for high quality	66	8	38	28
3.	Description of data analysis	61	19	49	38
10.	Clarity of writing	37	18	23	41
	Question B				
4.	Goals of preparing for lab	64	7	36	18
5.	Procedures for preparing for lab	8	55	5	64
6.	Application to specific experiment	61	14	28	26
11.	Clarity of writing	43	17	18	33
	Question C				
7.	Number of correct matches (0, 1, 3)	23	32	21	36
8.	Accuracy of chemistry	57	8	41	18
9.	Quality of logical reasoning	65	11	62	26
12.	Clarity of writing	59	8	51	23
	Average, measures 1–12 (%)	50	18	34	32
	Average length (page filled) (%)	< 25	> 50	< 25	> 50
13.	Length of response for Question A	36	12	13	26
14.	Length of response for Question B	32	10	8	33
15.	Length of response for Question C	31	15	23	26
	Average, measures 13–15 (%)	33	12	15	28

[a] The categories "Poor", "Fair", and "Good" sum to 100%.

Table 3. Independent Sample *t*-Tests for Comparison of Conventional and Experimental (Workshop) Lab Sections

Dependent Measures	Lab Type	Mean	SD Values[a]	*t* Values	*p* Values
Question A					
1. Description of experimental procedure	TA	1.67	0.75	2.11	0.036
	UTU	1.97	0.84		
2. Awareness of factors for high quality	TA	1.42	0.64	3.28[b]	0.002
	UTU	1.90	0.82		
3. Description of data analysis	TA	1.58	0.80	1.89[b]	0.063
	UTU	1.90	0.94		
Question B					
4. Goals of preparing for lab	TA	1.43	0.63	3.19	0.002
	UTU	1.82	0.72		
5. Procedures for preparing for lab	TA	2.47	0.65	1.03	0.304
	UTU	2.59	0.59		
6. Application to specific experiment	TA	1.52	0.73	3.31	0.001
	UTU	1.97	0.74		
Question C					
7. Number of correct matches	TA	1.09	0.74	0.45	0.654
	UTU	1.15	0.74		
8. Accuracy of chemistry	TA	1.51	0.65	2.03	0.044
	UTU	1.77	0.74		
9. Quality of logical reasoning	TA	1.46	0.69	1.18[b]	0.243
	UTU	1.64	0.87		

[a] Standard deviation; [b] Shows heterogeneity of variance; adjusted *t* used for these comparisons.

Table 4. *t*-Tests Comparing Conventional and Workshop Sections by Clarity of Writing and Length of Written Response

Dependent Measures	Questions	Lab Type	Mean	SD Values[a]	*t* Values	*p* Values
Clarity of writing (10–12)	A	TA	1.82	0.72	2.63	0.01
		UTU	2.18	0.79		
	B	TA	1.73	0.73	3.11	0.002
		UTU	2.15	0.71		
	C	TA	1.50	0.65	1.52	0.13
		UTU	1.72	0.83		
Length of response (13–15)	A	TA	1.76	0.65	3.91	<0.001
(Text + Equations)[b]		UTU	2.26	0.68		
	B	TA	1.78	0.61	4.19	<0.001
		UTU	2.26	0.60		
	C	TA	1.83	0.66	0.96	0.13
		UTU	2.03	0.71		

[a] Standard deviation; [b] Length of response is the percentage of a page filled, with 1 = 0–25% filled, 2 = 26–50% filled, and 3 = over 50% filled.

approaching significance ($p < 0.063$). For each measure evaluated, the direction of the mean difference always favored students in the Workshop labs, even when the means did not differ statistically.

The Workshop students performed very well on the Clarity of Answer and Length of (Written) Response measures for Questions A and B, but did not differ significantly on Question C. This may have been due to Question C's difficulty or it may reflect the fact that, because a portion of the question could be answered with equations, the question provided fewer opportunities for writing text.

Further analysis indicated that across instructional groups, students who scored well on a question filled more of the page when answering it ($p < 0.0001$).

Discussion

The results of both our quantitative analyses (summarized in Tables 2–4) and our review of the content of students' written exam answers illustrate several ways in which chemistry lab students in the Workshop sections perform at a higher level, on average, than those in conventionally run labs. These results confirm our informal observations of the UTU lab program over several years: no area of knowledge has emerged in which UTU students perform *less* well than students trained conventionally.

Although our pattern of results is both consistent and promising, we also considered the possibility that the observed differences between our experimental and control groups arose not from the experimentally created laboratory conditions, but from uncontrolled differences in the backgrounds of the two student groups. We did several comparisons of the two groups to further assess this alternative. These analyses revealed that most (about 70%) of the students in both the experimental and control groups were in their first term in college and that the two groups had very similar average SAT scores. Moreover, the performance of first-year students on the lab exam did not differ significantly from that of the other students, nor was there a significant effect of gender.

We also attempted to rule out the possibility that differences in the chemistry lecture sections attended by the students in this study accounted for our results. There are multiple lecturers and lecture sections in general chemistry each term. For the period covered by the project, most students in the experimental lab sections attended the lecture sections of one of the authors (MFG); however, the majority of the students in those lecture sections attended TA-led lab sections, including one of the six control sections in Phase II of the study and three of the TA-led sections in Phase I. In both the study reported here and in our less formal observations since 1998, we have found no clear connection between the performance of students in TA-led lab sections and the lecture section which they attended. The available evidence also suggests that, in terms of their performance in subsequent organic chemistry courses, there is no significant difference between the students in MFG's general chemistry lecture section and those in other lecture sections.

One further comment is relevant to this discussion. In our previous less formal evaluations of lab exam performance, exam questions that dealt with standard topics taught in chemistry lecture yielded no significant differences, on average, between students in UTU-led and TA-led lab sections. In fact, as stated earlier, it was this lack of difference that led us to focus on important skills that can be learned via lab, yet which are *not* well addressed in the conventional chemistry lecture. In short, we consider other explanations implausible and feel confident that our results are measuring the effects of the chemistry laboratory experiences of the students involved.

Our results, particularly for Questions A and B, suggest the greater proficiency of Workshop students in mastering both general (communications) skills and two of the four critical learning skills: learning skill I, the ability to gain global knowledge of an entire experiment, and learning skill II, the ability to assess the quality of the experimental results.

General communication skills were best assessed by our index of writing clarity (measures 10–12 in the Tables), which differed significantly between groups for Questions A and B, but not C. Learning skill I was most directly assessed by students' descriptions of the experimental procedure and data analysis in Question A (measures 1 and 3), and also by their responses to the last part of Question B (measure 6), which asked students to discuss a specific experiment. Learning skill II was best reflected in the second part of Question A (measure 2), which tested students' awareness of the factors needed to ensure a high quality result in the experiment. Most *poor* rankings for this measure arose because students did not specifically address this portion of the question.

We suspect that the emphasis on learning skill II in our peer-led labs leads Workshop students to approach many aspects of lab experiments more critically, and to read instructions more carefully. The impact of this emphasis is illustrated by our Question B results (measures 4 and 6): students in the control group failed to read the question carefully and often described the goal of an experiment rather than the goal of preparing for lab. The difference on this measure is one of the largest found between Workshop and conventional students, and confirms informal observations of past lab exam responses for the two lab groups. For example, when asked (in the Spring of 1999) to discuss the advantages of pooled data, Workshop-trained students were much more likely to emphasize the improved accuracy of pooled data (68%, vs 20% of conventionally trained students) instead of its value as a timesaving practice (27%, vs 43% of conventionally trained students).

No advantage for UTU labs was demonstrated for learning skill III, the ability to explain and draw conclusions from data, which was tested most directly in Question C (measures 7–9): the performance of students in both conventional and workshop labs proved disappointing. Learning skill IV, the ability to apply one's knowledge to new situations, although relevant to both Questions B and C (measures 6–7), was not prominently tested by either question. The present study must therefore be considered inconclusive with respect to this skill.

The difference in the length of the written answers found here between Workshop students and control group students has also been seen in previous, less formal analyses of the lab exams. The strong correlation of answer length with answer quality ($p < 0.0001$) suggests that students who knew more wrote more. However, it is also possible that the longer answers by the Workshop students reflect their greater motivation to do well on the lab exam. A further check of the writing showed that Workshop students' longer answers did *not* generally result from repetition or the inclusion of irrelevant information. Rather, most of the shorter answers from both groups of students were clearly incomplete, and omitted some of the expected information.

Unreported analyses of student performance on the lab exam indicated that there were large differences between individual sections of lab, but confirmed that students in the Workshop sections performed as well as the best of the conventionally trained students. The general success of the implemented Workshop approaches has led us to begin extending these approaches, where possible, to our conventional labs, where we believe they will exert comparable positive impacts.

Although the present study does not directly address which aspects of the Workshop Chemistry model are responsible for the observed improvements in student performance, several suggestions may be offered.

First, the teacher-to-student ratio is much better in the Workshop (UTU) sections, since there are several instructors, not just one. This allows for much more interaction, the adoption of a small group-based approach in the pre-lab introduction, and the widespread use of structured student-instructor discussions at the lab bench. Second, although both graduate TAs and undergraduate mentors attended weekly training sessions, the sessions were separate for the two instructor groups, and structured rather differently.[2] The undergraduate mentors' sessions emphasized the four learning skills and the need to involve the students actively. Third, the UTUs were closer in age and experience to the students, and often adopted a less authoritative, more mentoring role. Because they had completed the course themselves rather recently, it may have been easier for them to anticipate problem areas. The UTUs also often worked together as a collaborative team, exploiting their wide range of backgrounds, skills, and personalities, and modeling the value of collaborative teamwork.

Finally, the variation in performance across lab sections suggests that factors related to the individual instructor may also be important in predicting student outcomes. Clearly, teaching style can play a role, as described by Hilosky *(2).* Other more social or motivational aspects may also be relevant *(6).* It is noteworthy in this regard that students in the Workshop lab sections were, on average, more satisfied with their learning experiences than those in conventional lab sections, and this may have influenced their performance.[2]

In terms of the ongoing discussion concerning the relative effectiveness of expository and inquiry-style labs *(1),* the first three of the above factors would tend to promote a more active approach by students enrolled in Workshop sections. Although this is consistent with the aims of the inquiry model, it should be noted that the object of inquiry approaches is somewhat different than that of our UTU Workshops. Instead of discovering a law of chemistry, students in our Workshop labs have the goal of discovering their own effective, general approach to carrying out lab activities. This discovery involves them in constructing their own understandings of the four learning and understanding skills and acquiring the practical experience needed to apply them successfully.

Future research should focus on understanding why the UTU Workshop approach is effective and should address areas in which performance improvements are still needed, such as recall of factual information and the ability to argue logically from observations to conclusions.

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Notes

1. Multivariate analysis of variance was used to correct for the interdependence of the 15 comparisons and to assess the overall impact of instructional format across all measures, taken together. For this analysis, $F(15, 132) = 2.124$, $p = 0.012$. The separate t-test results for each comparison are reported in the tables, since they are equivalent to the univariate F values for a two-group comparison, and also allow automatic correction for differences in score variability, when needed.
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