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CO_2 Investigations: An Open Inquiry Experiment for General Chemistry

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Supporting Information

ABSTRACT: This paper presents a successful, free inquiry experiment in which students devise an experiment to measure carbon dioxide in an important chemical, biological, or environmental situation. Also discussed is rationale for adopting an open inquiry experiment and how it fits into the laboratory as a whole. Typical student projects are given, and data showing this experiment's success are presented and discussed.

KEYWORDS: *First-Year Undergraduate, Laboratory Instruction, Inquiry Based/Discovery Learning, Student Centered Learning, Hands-on Learning/Manipulatives, Applications of Chemistry, Gases*

BACKGROUND

Laboratory work is an important part of chemical education around the world. Yet laboratories taught in the conventional way often fail to engage students in the process of doing science.[1,2] For the past 25+ years, there have been increasingly frequent calls for inquiry-based learning[3−7] in both the classroom and in the laboratory. Hundreds of inquiry-based experiments have appeared in this journal and elsewhere. Laboratory courses based on inquiry have appeared[8−10] as have laboratory texts.[11−15]

Fundamentally, inquiry-based learning is student-centered and involves the instructor asking questions rather than presenting facts. The goal is that as students strive to answer questions they move toward taking ownership in their own learning. The best case inquiry-based experiments are like an art student facing a blank canvas with the challenge of painting what is in her mind's eye. The chemistry student must ask an appropriate question, design an experiment seeking its answer, and then carry out the experiment, analyze the data, and communicate the significant findings. Bruck, Bretz, and Towns[16] call this authentic inquiry.

At the freshman level, authentic inquiry presents three major challenges. Experiments are generally designed and sometimes mandated to cover specific chemical principles or laboratory techniques. Beginning chemistry students cannot be expected to be familiar with the laboratory techniques needed to design an experiment or even how to go about designing an experiment. Lastly, beginning students are seldom aware of the safety issues inherent in working with specific substances. The first of these challenges can be met by reimagining the purpose of the laboratory in chemical education. It is frequently also possible to cover concepts and techniques in other ways. The second and third challenges are more fundamental and are best met through education.[17]

The vast majority of laboratory texts and experiments used in chemistry involve structured or at best guided inquiry.[16] Adopting the language of ref 16, laboratory activities can be ranked on the basis of amount of structure given in the written experiment. Arranged from most to least structure these are confirmation, structured inquiry, guided inquiry, open inquiry, and authentic inquiry. Confirmation is precisely that, the confirmation of previously known information. Structured inquiry gives students the problem, detailed background, and experimental procedures and outlines the data analysis. The majority of chemistry experiments currently in use involve structured inquiry. Guided inquiry gives the problem, background, and procedures. Open inquiry provides only the problem and background. Authentic inquiry provides none of these attributes. Authentic inquiry involves student-initiated experiments.

Using the methods of ref 16, an analysis of over 100 laboratory activities published within the past 10 years in this journal with the term "inquiry" as a key word, or in the title or abstract, was done. This showed that just over 90% of these inquiry-based works use guided inquiry. Nine used open inquiry[18−26] and only two authentic inquiry.[27,28] Both of these deal with upper-level, student-initiated research projects. With one exception,[11] the inquiry-based laboratory texts available are predominantly guided inquiry.[12−15]

Guided inquiry typically involves a specific chemical concept and provides the basic background and procedures for the experiment. In some versions of guided inquiry, students apply these procedures to a new situation. Such experiments overcome all three challenges identified above. However, providing procedures allows students to follow these directions, even for a new situation, with little thought to what they are doing or what their results tell them. To the extent that this occurs, it leads to diminished student engagement with the experiment. In open and authentic inquiry, the student is responsible for devising their procedure, which necessitates greater engagement.

Which is the better choice? From a pedagogical perspective, the greater student engagement with open or authentic inquiry suggests that they would be the best choice. From a practical perspective, guided inquiry gives students help with procedural and safety details they are unlikely to know, making the

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experiment doable. What do students say? Surveys of high school[29] and college, general chemistry[30] students show that they favor guided over open inquiry experiments. Student comments suggest that they like having the procedures given because it requires less thinking on their part. This is consistent with observations[31] that, given two choices of equal point value, students generally choose the easier path. Students also perceive that they learn more from guided inquiry experiments than open inquiry experiments.[30] This is consistent with research[32] on student interactions, showing that guided inquiry favors a more exploratory (versus procedural) approach to an experiment than either higher (open) or lower (structured) levels of inquiry. Given these findings, it seems that we should stop our inquiry-based laboratories at guided inquiry. The counter argument is that we generally want our students to think more deeply even if they would prefer not to. Open inquiry requires students to engage in the kinds of thinking we ultimately want students to master.

This is the reasoning that leads to the development of our inquiry-based laboratory, and it leads to a dilemma. How could an open inquiry experiment be used if students had insufficient background to do such an experiment? One solution to this dilemma involves beginning a laboratory with a guided inquiry approach, expecting more independent thinking from the students as the semester progresses, and ultimately ending with an open inquiry experiment. This is the design philosophy that informed the development of the inquiry laboratory for General Chemistry I and the open inquiry experiment described here. The rationale for including an open inquiry experiment is two-fold. The first is to prod students to begin thinking more independently. The second is to assess their degree of independent thinking.

Designing a laboratory to lead up to an open inquiry experiment requires considering the laboratory as a whole and not merely a series of independent experiments. It also necessitates a complete rethinking of the laboratory experience.[33] Fortunately, there is considerable help available from inquiry-based laboratory texts[11−15] and the literature.[8,9,17,27,34,35]

How would you design an open inquiry experiment for students with limited background knowledge? Such an experiment must

- Focus on something about which students have previous knowledge
- Pose no significant safety issues
- Be easily accomplished
- Require little if any "extra" equipment or chemicals.

These are rather restrictive requirements, but it occurred to the author that such an experiment had already been designed for an environmental chemistry class.[36] That experiment is the basis for "CO_2 Investigations", which now has been used for 10 semesters in our General Chemistry I, inquiry-based laboratory. The laboratory uses the Volz and Smola[12] text. This experiment begins shortly after midterm when students are familiar with the Vernier equipment and have completed several experiments with increasing expectations of independent thinking.

■ THE EXPERIMENT

Mechanics

Our laboratories are limited to 24 students and are typically filled. Students work in groups of three or occasionally two on this experiment. It has been run in 13 laboratory sections over the last 10 semesters. The experiment is not used in summer school due to time limitations.

Methods

After students are familiar with the basics of using the Vernier equipment, they are given a challenge. It begins by showing them carbon dioxide and oxygen detectors and performing a very simple experiment, showing the use of both. They are then given the following problem: "Find an interesting chemical, biological, or environmental issue involving carbon dioxide. Devise a researchable question relative to it and an experiment to provide the data necessary to answer your question." (The complete assignment is available as Supporting Information.)

Students are expected to find their own experiment. They are asked to generate one or more realistic researchable questions. The questions must be approved by the laboratory instructor who typically discusses the practicality of each question the students pose, helping students choose the best question. The instructor also works with students as needed to develop a sound experiment, including the safety concerns their experiment may have and teaching them how to program the LabQuest data logger appropriately for their experiment.

Once students have a fully developed experiment, including safety considerations, they can sign up for specific dates and times to pick up the necessary equipment and to return it. They complete the experiment on their own outside of the laboratory. When the equipment is returned, the students are asked if they have any questions regarding the analysis of their data. Even with all this help, the students still have room to fail. Failure typically means that students have not collected the data necessary to fully answer their researchable question. The net result is that students take ownership in their experiments, often leading to profound learning opportunities.

Because of limited equipment and because some of the student's experiments may take a week or longer, there is generally 3−4 weeks between the beginning of this experiment and its conclusion. The conclusion involves both a laboratory report and an oral presentation to the class. The oral presentations are evaluated using a specific rubric by the rest of the class. This rubric prompts students to write down questions which they are encouraged to ask after each presentation. If no student asks how an experiment could be improved, the instructor should. In their written reports, students are asked to consider what worked well, what did not, and then to explain how they would improve their experiment if they had a chance to repeat it. Unfortunately, there is insufficient time in the class for this repetition.

Box 1 illustrates the wide range of experiments students devise. Some of these experiments are actually ill-founded. One set of students looking at car exhaust hypothesized that cars would emit more CO_2 while the engine warms up. They were really thinking about CO. They were allowed to do the experiment and challenged to consider why they saw little difference. They eventually recognized the CO/CO_2 confusion and asked how they might test for CO. In the process, they probably learned more than students whose experiments showed them exactly what they had expected. Other students repeat common experiments, for example, studying both oxygen and carbon dioxide levels in the presence of a plant. When a student project revisits a well-known experiment, it is still new to the students involved and they generally learn a great deal. We have observed that virtually any experiment, simplistic or grand, or even those that failed caused the students

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to think carefully about the problem they choose and exhibit significant learning in the process.

Box 1: Representative Student CO_2 Experiments

Measuring CO_2 and O_2 levels during photosynthesis and respiration
Measuring CO_2 and O_2 levels in sealed chambers with
Decaying plant material
Decaying mice
Measuring CO_2 production in soils
Measuring CO_2 evolved from soft drinks as a function of time and temperature
Measuring CO_2 in exhaust plumes from
Cars, gas powered and hybrid
Trains, both empty and full coal trains
Investigating different materials for CO_2 scrubbers
Is a swamp a net CO_2 consumer or producer?
Measuring CO_2 dissolution by seawater
Will iron(III) increase CO_2 uptake in water?
Measuring CO_2 in the air above wastewater treatment basins
Measuring exhaled CO_2
When waking and sleeping
By asthmatics
By smokers and nonsmokers
By persons during different levels of exertion
By dogs of different body mass
Measuring CO_2 levels in full and empty classrooms
Measuring CO_2 levels vs time in a dance studio
Measuring CO_2 levels under an atmospheric inversion as it forms and dissipates

■ HAZARDS

In this experiment, students design and carry out their own experiments. With no set experiment, there can be NO specific set of safety considerations. With prompting as necessary from the instructor, the students are responsible for recognizing and appropriately dealing with the safety issues in the experiments they plan.

■ DISCUSSION

In eight sections of the inquiry laboratory over six semesters, a short questionnaire was added to the course evaluations. 87.7% of students (N = 203) choose this experiment as their favorite in the class. No students listed it as their least favorite. 84.2% of students indicated that they learned the most from this experiment. These results seem in contrast to the work of Chatterjee et al.,[30] whose results show that students favor guided inquiry over open inquiry. We have not done a careful study of students' preferences, such as that of Chatterjee et al., and have no data to indicate why our students feel differently about open inquiry, but we suspect there may be three reasons. The first stems from the lab design, which gradually expects more independent thinking from students leading up to this open inquiry experiment. The second is that this experiment deals with real world issues. The third is that through the oral presentations students get to hear about and discuss several different carbon dioxide experiments.

A common lab practical exam was given in both the inquiry-based lab and one taught in "the regular way" each semester for 2 years.[37] Students in both versions of the laboratory had the necessary background to answer all of the questions. Two questions from the first version of this exam[38] are germane to this experiment. Table 1 shows the results of these question for two sections of each course in the first year the inquiry laboratory was taught.

Table 1. Partial Results from a Common Laboratory Exam

	Comparison of Average Scores		
Topics[a] (points)	Inquiry laboratory, N = 43	Regular laboratory, N = 39	Statistical confidence of difference
Design a simple experiment (15)	11.9	5.5	95
Conceptual data analysis (10)	8.2	5.8	80

[a]Two questions from the exam were germane to the open inquiry experiment.

These results show that students in the inquiry-based laboratory scored significantly higher than their counterparts on questions requiring independent thinking. Instructor observations show that students in the inquiry lab were also generally more comfortable answering questions regarding their experiments. (Both assessment tools are available as Supporting Information.)

There are other, less concrete, markers. This experiment is generating interest in our campus. Recently, during preregistration for the next semester, the instructor was asked "will we do the CO_2 experiment next semester?" The Fall 2013 oral presentations are the basis for a University of North Carolina Pembroke news release.[39] It also has a lasting effect. Several colleagues have commented that students who have taken the inquiry-based laboratory including this experiment are generally more comfortable in new laboratory situations and often learn more from them than other students. It has been observed that, even several semesters later, students from this lab continue to be engaged in their laboratory work, digging deeper into their experiments than most other students.

■ CONCLUSION

We have presented a successful, open inquiry experiment for first term, general chemistry. Results show that students enjoy this experiment and learn from it. Instructors' observations indicate that even several semesters after taking this laboratory students tend to work more independently in the laboratory and are more deeply and intellectually engaged in the experiments.

The benefits are clear. Having students conceive, design, and carry out their own experiments is possible in the general chemistry laboratory in carefully controlled circumstances. Such experiments go beyond the typical laboratory experience, making it a true inquiry activity. Perhaps most importantly, through such experiments, students work independently and learn from the process—exactly what is desired from the laboratory. This open inquiry-based CO_2 experiment is a success and plays a significant part in overall success of the inquiry laboratory.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/ed5006932.

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Student assignment (PDF, DOCX)

Instructor's notes (PDF)

Report and oral presentation rubrics (PDF, DOCX)

Assessment tools, including both the student survey and the laboratory final exam (PDF)

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Notes

The authors declare no competing financial interest.

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(38) In the third semester that this exam was used, we had evidence that some students may have seen the exam from a previous semester or the earlier section of the class. It was significantly revised for the fourth semester.

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