Preparing Students To Benefit from Inquiry-Based Activities in the Chemistry Laboratory: Guidelines and Suggestions

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Inquiry has been defined as "a pedagogical method that combines hands-on activities with student-centered discussion and discovery of concepts" *(1),* and national criteria describe inquiry-based instruction as a crucial technique for teaching science, especially in the laboratory *(2–4).* French and Russell *(5)* write

> Inquiry-based instruction places more emphasis on the students as scientists. It places the responsibility on the students to pose hypotheses, design experiments, make predictions, choose the independent and dependent variables, decide how to analyze the results, identify underlying assumptions, and so on. Students are expected to communicate their results and support their own conclusions with the data they collected.

These are the definitions and descriptions for inquiry-based instruction around which the following discussions and suggestions will be based.

In the quest to prepare students for laboratory work, many strategies have been reported in the literature over the past decade *(6–13).* However, despite research-based methodologies focused on priming students for the laboratory, it has been reported in the literature that inquiry-based laboratory activities leave many students in the dark *(14–15),* and underprepared students and instructors have experienced negative results when attempting inquiry-based activities *(16–17).* In addition, if students believed that their laboratory results would not be evaluated meaningfully, then they trivialized laboratory activities *(18).* A recent publication addresses the troublesome issues related to teaching by inquiry and provides a rubric to connect inquiry terms to the level of inquiry facilitated by the laboratory experiment or activity *(19).* This paper presents some suggestions for instructors to prepare students for inquiry-based laboratory activities and explain their use in the laboratory. The model that follows presents ideas for instruction before, during, and after inquiry-based activities have been introduced into the laboratory curriculum. The goal is to assist instructors of laboratory courses in implementing inquiry by providing examples and ideas.

Teaching and Assessing Content Mastery

Provide Sufficient Subject Matter Background

To participate in meaningful learning, students must first possess proper background knowledge to which new learning can be connected *(20–21).* If laboratory is an environment for learning, and students are expected to successfully complete an inquiry-based activity, then students must possess appropriate prior knowledge of the topic to be investigated in laboratory *(22–23).* However, this background knowledge should not be mistaken as knowledge of the outcomes of the experiment being conducted. Instructors should ensure that sufficient content material has been taught in lecture or in previous labs.

One criterion of inquiry-based instruction is that students do not know the outcomes of their experimental investigations before embarking on them *(5).* Thus, appropriate background knowledge that would not hinder the findings of an inquiry-based activity could be something as simple as the following example: prior to a laboratory investigation of reactions in aqueous solution, ensure that students have received instruction on appropriate concepts, such as electrolytes, solubility, and representing the results of a precipitation reaction as a net ionic equation. However, solubility rules should not be covered. This way, students can carry out an inquiry-based investigation on reactions in aqueous solution while not knowing the results of the experiment in advance. An inquiry-based investigation involving such reactions might ask students to determine the products of reactions and the solubilities of the salts produced. Further, students could build solubility rules based upon experimental observation. They could also be allowed to generate their own laboratory procedure for testing combinations rather than following an instructor-provided experimental procedure that delineated every step.

Students must also possess sufficient knowledge of the procedures and techniques for the laboratory and be able to use them *(24).* Many manuals devote several experiments solely to building competence in laboratory techniques for use in later activities. For example, Wink, Gislason, and Kuehn in their preface to *Working with Chemistry: A Laboratory Inquiry Program (25)* write

> We do not expect students, for example, to be able to design an acid–base experiment on the first day they use a buret. But within a short timespan, they will be expected to carry out the procedure to meet certain parameters.

Thus, instructors of laboratory courses should try to ensure that the students master the necessary techniques before allowing students to carry out an inquiry-based activity independently. Returning to the reactions in aqueous solution example, appropriate technique mastery for this inquiry-based activity would include knowledge of any apparatus used and safety issues. Of course, the technique mastery level on the part of the student would be more advanced for activities using more sophisticated techniques.

Assess Students' Conceptual Knowledge Skills prior to Undertaking the Inquiry Activity

This recommendation is related to the previous suggestion, and addresses the notion that students should not enter the laboratory without a proper understanding of the concepts involved in the experiment to be performed *(26).* Many students are able to perform algorithms accurately in the classroom with little conceptual knowledge of the topic while possessing misconceptions about the chemical world *(27).* Though seemingly prepared for inquiry-based laboratory work from an algorithmic perspective, the inadequacy of necessary conceptual skills may impede student progress on an inquiry-based experiment. If necessary, engage students in activities to build concepts first.

To determine whether students' background knowledge is prepared for lab, assess their understanding formally or informally. An easy approach to formally assess students' knowledge is to ask definition, algorithmic, or higher-order questions as described by Robinson and Nurrenbern *(28).*

Informal assessments can be performed in a variety of ways, such as engaging students in think-pair-share activities, in which students are given the opportunity to answer a question first independently, discuss the response with a partner, and finally share responses with the entire class *(29).* Other examples for informal assessment include electronic response system questions, homework and collaborative group discussions such as the methods described in ref *30.* More formal assessments include quizzes and exams. If students' mastery of the material is insufficient, then devoting more time to the topic before students embark on an inquiry-based activity is warranted.

Modifying Pedagogical Strategies

Transition Students Gradually to Inquiry-Based Activities

To make a laboratory curriculum more inquiry-based we suggest that instructors start small. Jennifer Lewis expressed this idea succinctly *(17)* in her case study of mini-projects:

> There is a clear need for some form of labwork which can help undergraduate students to make the transition from set practicals which are designed to develop their technical skills to open ended investigations which are designed to develop their research skills.

Research has demonstrated that after years of traditional lab experiences students cannot simply be thrust into an inquiry-based activity with little prior experience in solving open-ended problems, and achieve success *(17, 31–32).* However, there are activities that may influence student success in carrying out inquiry-based experiments. For example, students could design a small set or subset of procedures in an experiment. Alternatively, students could develop methods by which data would be analyzed rather than having the instructor specify every calculation and manipulation. Students could be asked to explain their approach and clearly connect the goal of the experiment to the data analysis and interpretation.

Adopt a More Facilitative Role in Laboratory

Hilosky, Sutman, and Schumuckler noted in this *Journal* that, "for the most part, college students enrolled in beginning chemistry courses do not, during laboratory-based experiences, learn to follow directions. Instead, they learn to depend excessively upon oral directions presented by the instructor in response to their queries" *(31).* When the lab instructor is the sole source of knowledge and troubleshooting, students tend to simply rely on instructors to solve their problems, and after developing such a relationship, may be uncomfortable or confused by independently performing experiments without the instructor *(17, 32).* During the transition from traditional to inquiry-based activities in lab, instructors can begin to adopt more facilitative roles by avoiding explicitly answering students' questions with direct answers, and guiding students with questions to lead them towards developing a response or solution on their own. In addition, suggestions for supporting teaching assistants in inquiry-based activities are available in the literature *(5, 33–34).* Although these processes may initially frustrate students, persevering will help instructors coach students to rely on their peers or their teams, rather than their instructors, for solving problems.

Communicate Reasonable Expectations

Faculty can expect that students will need some time to learn how to successfully complete an inquiry-based experiment. Transitioning from traditional to inquiry-based laboratories is challenging for most students *(17, 32, 38).* Mohrig wrote in 2004 *(38)* that

> Students will need a little time to learn that they have to come to laboratory prepared to think, but once they have done so, they enjoy their labs much more. It has already become easier as students are exposed to more inquiry-based labs in their introductory chemistry courses.

In other words, students' first attempts at inquiry-based activities will most likely be more difficult than with the laboratory activities they have completed in the past.

Clearly communicating expectations is key to the successful transition of the student. For example, faculty can emphasize that the process of formulating questions and experimental procedures and communicating results is more important than simply getting "an answer". A grading scheme or rubric can be distributed in advance that describes the assessment criteria. Points can be earned for each step or activity such that the students know their efforts will be rewarded. Finally, a timeline can be given for completion of work so that students can make the decision to repeat experiments.

Developing and Supporting New Roles for Students

Promote and Guide Student-Designed Inquiry

Allow students to design their own research question and write a method for approval by the instructor. One criterion for inquiry presented in the literature is that students have an opportunity to develop research questions and procedures independently *(5, 19).* If students are properly prepared to carry out a higher-level inquiry activity with a greater degree of student independence, then they will benefit from the process *(14, 32, 35–36).* For example, students could be given a general, broad area to research, such as determining the vitamin C concentration of foods. Students could develop their own research question, (i.e., varying kinds of food and conditions under which it would be cooked or kept), and create a data collection and analysis plan to answer it. The instructor could help students refine their questions and ensure that the experimental procedures and analyses would address the student-generated questions.

C. A. R. Berg commented upon the completion of an open-ended inquiry project *(14):*

> Obviously they had to be better prepared because that was part of their task but they stayed with their experiments because they found it stimulating to get results from something that they had planned themselves.

Incorporate Student-Led Presentations and Discussions

A crucial step in the practice of science is presentation of data *(35–37);* yet, most chemistry laboratory manuals explicitly direct students how to present their findings of the laboratory. A criterion of inquiry-based instruction is allowing students to present their findings *(5),* and thus, to facilitate a greater degree of student independence, student groups can present their data and findings using strategies of their choice. One of the hallmarks of science is that explanations must be in agreement with the data collected and analyzed, and a characteristic of inquiry-based instruction is students' freedom to present and defend their findings *(5).* Thus, students can be challenged to explain their reasoning and support their findings. Engagement in activities of this type can extend the inquiry nature of the laboratory without the standard post-laboratory notebook questions.

Conclusion

Inquiry-based methodologies for laboratory hold a highly regarded position in science education *(2–4),* and will continue to be part of chemistry education. Using recommendations and findings from previous applications and studies on inquiry-based experiments can help faculty implement these types of labs with greater success. Key student activities include developing:

- Foundational knowledge required for engagement in inquiry activities
- Appropriate laboratory skills
- Independence through generation of experimental procedures, methods of analysis, and communication and defense of results

For faculty, key activities include:

- Transitioning to a more facilitative approach in lab
- Guiding students in developing their own research questions, procedures, and analysis
- Communicating clear expectations to students

In addition, faculty should carefully consider the political landscape of the department and course in which inquiry-based activities will be implemented. Buy-in and active support by faculty colleagues, staff, and teaching assistants of "new" laboratory approaches will drive forward such initiatives and increase the probability of their success. Implementing inquiry in a piecemeal fashion may create unintended consequences including abandonment of inquiry-based approaches and a return to the "old" way of conducting laboratories. Thus, for sustained implementation, it is vital to gain commitments from faculty who teach the course, those who implement the curriculum, and faculty who teach successive courses.

Literature Cited

1. Uno, G. E. *Bioscience* **1990,** *40,* 841–843.
2. National Research Council. *National Science Education Standards;* National Academies Press: Washington DC, 1996.
3. National Research Council. *Inquiry and the National Science Education Standards;* National Academies Press: Washington, DC, 2000.
4. Rutherford, F. J.; Ahlgren, A. *Science for All Americans;* Oxford University Press: New York, 1990.
5. French, D; Russell, C. *Bioscience* **2002,** *52,* 1036–1041.
6. Carnduff, J.; Reid, N. *Enhancing Undergraduate Chemistry Laboratories: Pre-Laboratory and Post-Laboratory Exercises;* Education Department, Royal Society of Chemistry: London, 2003.
7. Isom, F. S.; Rowsey, S. E. *J. Res. Sci. Teach.* **1986,** *23,* 231–235.
8. Kirk, M. K.; Layman, J. W. A Pre-Lab Guide for General Chemistry: Improving Student Understanding of Chemical Concepts and Practices. Paper presented at the 69th Annual Meeting of the National Association for Research in Science, St. Louis, MO, April, 1996.
9. McKelvy, G. M. *Univ. Chem. Educ.* **2000,** *4,* 46–49.
10. Nicholls, B. S. *Univ. Chem. Educ.* **1999,** *3,* 22–27.
11. Pickering, M. *J. Chem. Educ.* **1987,** *64,* 521–523.
12. Rollnick, M.; Zwane, S.; Staskun, M.; Lotz, S.; Green, G. *Int. J. Sci. Educ.* **2001,** *23,* 1053–1071.
13. Sirhan, G.; Reid, N. *Univ. Chem. Educ.* **2001,** *5,* 52–58.
14. Berg, C. A. R.; Bergendahl, V. C. B.; Lundberg, B. K. S. *Int. J. Sci. Educ.* **2003,** *25,* 351–372.
15. Germann, P. J. *J. Res. Sci. Teach.* **1989,** *26,* 237–250.
16. Hancock, C.; Kaput, J. J.; Goldsmith, L. T. *Educ. Psychol.* **1992,** *27,* 337–364.
17. Lewis, J. The Effectiveness of Mini-Projects as a Preparation for Open-Ended Investigations. In *Teaching and Learning in the Science Laboratory,* Psillos, D., Niedderer, H., Eds.; Kluwer Academic Publishers: Norwell, MA, 2002; 139–150.
18. Johnstone, A. H. *J. Comput. Assist. Lear.* **1991,** *7,* 75–83.
19. Bruck, L. B.; Bretz, S. L.; Towns, M. H. *J. Col. Sci. Teach.* **2008,** *38,* 52–58.
20. Ausubel, D. P. *J. Gen. Psychol.* **1962,** *66,* 213–224.
21. Ausubel, D. P.; Novak, J. D.; Hanesian, H. *Educational Psychology: A Cognitive View,* 2nd ed.; Holt: New York, 1968.
22. Germann, P. J.; Haskins, S.; Auls, S. *J. Res. Sci. Teach.* **1996,** *33,* 475–499.
23. Reid, N.; Shah, I. *Chem. Educ. Res. Pract.* **2007,** *8,* 172–185.
24. Meester, M. A. M.; Maskill, H.; Maskill, R. *Int. J. Sci. Educ.* **1995,** *17,* 705–719.
25. Wink, D. J.; Gislason, S. F.; Kuehn, J. E. *Working with Chemistry: A Laboratory Inquiry Program,* 2nd ed.; W.H. Freeman and Company: New York, 2005, p ix–xi.
26. Johnstone, A. H.; Watt, A.; Zaman, T. U. *Phys. Educ.* **1998,** *33,* 22–29.
27. Nakhleh, M. B.; Lowrey, K. A.; Mitchell, R. C. *J. Chem. Educ.* **1996,** *73,* 758–762.
28. Nurrenbern, S. C.; Robinson, W. R. *J. Chem. Educ.* **1998,** *75,* 1502–1503.
29. *Experiences in Cooperative Learning: A Collection for Chemistry Teachers,* Nurrenbern, S. C., Ed.; Institute for Chemical Education: Madison, WI, 1995.
30. Kogut, L. S. *J. Chem. Educ.* **1997,** *74,* 720–722.
31. Hilosky, A.; Sutman, F.; Schumuckler, J. *J. Chem. Educ.* **1998,** *75,* 100–104.
32. Modell, H. I. *Adv. Physiol. Educ.* **1996,** *15,* S69–S77.
33. Volkmann, M. J.; Zgagacz, M. *J. Res. Sci. Teach.* **2004,** *41,* 584–602.
34. Roehrig, G. H.; Luft, J. A.; Kurdziel, J. P.; Turner, J. A. *J. Chem. Educ.* **2003,** *80,* 1206–1210.
35. Tien, L. T.; Rickey, D.; Stacy, A. M. *J. Col. Sci. Teach* **1999,** *28,* 318–324.
36. Guillon, A; Séré, M. G. The Role of Epistemological Information in Open-Ended Investigative Labwork. In *Teaching and Learning in the Science Laboratory,* Psillos, D., Niedderer, H., Eds.; Kluwer Academic Publishers: Norwell, MA, 2002; pp 121–136.
37. McGinn, M. K.; Roth, W. *Educational Researcher* **1999,** *28,* 14–24.
38. Mohrig, J. R. *J. Chem. Educ.* **2004,** *81,* 1083–1085.

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