Characterizing the Level of Inquiry in the Undergraduate Laboratory

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Ann Cutler served as column editor for this contribution to the Research and Teaching column of the Journal of College Science Teaching

Discrepancies abound in use of the word "inquiry." We propose a quantitative rubric to characterize inquiry in undergraduate laboratories.

A common goal for science educators is to engage students in inquiry; however, many factors complicate the completion of such a task. A primary problem encountered by faculty facing this challenge is that the word "inquiry" is used ubiquitously throughout education literature, both as a style of teaching and as a method for conducting research (Flick 1995). This dualistic perspective can generate cognitive dissonance for faculty. How much direction is necessary? To what extent does the learner develop his or her own procedures and methods? How is student learning assessed? Are there different types or varying degrees of inquiry? We found such discrepancies in chemistry and were prompted to delve further into other science disciplines (Fay et al. 2007). Given the emphasis on inquiry in the National Science Education Standards (NRC 2000), we probed the K–12 literature, uncovering a myriad of usages for the word "inquiry."

In this paper, we propose a quantitative rubric designed to characterize the level of inquiry in laboratory activities and laboratory curricula. We do not wish to answer the question, "What is inquiry?" but rather, provide a tool for identifying its varying degrees of student independence.

Definitions of inquiry from the literature

The literature on inquiry differs in usage between practitioners in secondary education settings (Colburn 2000; Martin-Hansen 2002; Windschitl and Buttemer 2000) and instructors in undergraduate settings (Domin 1999; Farrell, Moog, and Spencer 1999; Mohrig, Hammond, and Colby 2007; Pavalich and Abraham 1977). Both audiences use unique definitions and criteria for inquiry, with little overlap between them. Brown et al. (2006) tactfully describes this dilemma, writing,

"What makes this research difficult to understand is the lack of agreement about what constitutes an inquiry-based approach. The bulk of the research has taken place in precollege classrooms examining the outcomes of various blends of inquiry-based instruction. These studies are hard to compare given the differing meanings for inquiry that have been employed" (p. 786).

Inquiry and the National Science Education Standards (NRC 2000) presents inquiry as a continuum, and Brown et al. (2006) extrapolates this continuum with a figure moving from more to less guidance. While both Brown et al. (2006) and the NRC (2000) provide frameworks for inquiry, no concrete definitions concerning discrete levels of inquiry or terminology associated with inquiry are explained in detail. Colburn (2000) writes, "Perhaps the most confusing thing about inquiry is its definition. The term is used to describe both *teaching* and *doing* science" (p. 42), and Anderson (2002) describes the body of literature concerning inquiry as "relatively non-specific and vague" (p. 4), commenting that "the research literature on inquiry tends to lack precise definitions" (p. 3).

Multiple modifiers for inquiry are quite common, including traditional inquiry, guided inquiry, structured inquiry, open inquiry, directed inquiry, inquiry learning, inquiry teaching, authentic inquiry, scientific inquiry, partial inquiry, and full inquiry (Abraham 2005; Anderson 2002; Bell et al 2003; Chinn and Malhotra 2002; Colburn 2000; Domin 1999; Eick and Reed 2002; Farrell, Moog, and Spencer 1999; Gaddis and Schoffstall 2007; Germann 1989; Germann, Haskins, and Auls 1996; Hancock, Kaput, and Goldsmith 1992; Martin-Hansen 2002; Kyle 1980; NRC 2000; Mohrig 2004; Mohrig, Hammond, and Colby 2007; Pavalich and Abraham 1977; Schwartz, Lederman, and Crawford 2004; Windschitl 2004; Windschitl and Buttemer 2000). The meanings of these terms are wide ranging. For instance, a review of the literature reveals multiple definitions for guided inquiry that vary by author and journal of publication. One precollege teacher describes guided inquiry as an investigation where "the teacher provides only the materials and problem to investigate. Students devise their own procedure to solve the problem" (Colburn 2000). However, an undergraduate-directed source claims, "Guided inquiry or discovery experiments are designed to lead students to hypothesis formation and testing… The student begins by collecting data and looking for trends or patterns. Ideally, a hypothesis is formed and then tested. The goal is to make connections between observations and principles" (Farrell, Moog, and Spencer 1999, p. 572). The descriptions of guided inquiry employed by these two authors are not in accord; one focuses on the student development of procedures, while the other focuses on hypothesis formation and testing.

Consequently, the uses and meanings of inquiry as modes of instruction and student investigation vary among authors and intended audiences. Texts and journals struggle to define inquiry in a way that can be used by both secondary school practitioners and university researchers. Because no universal, concrete definitions concerning the levels and terminologies of inquiry exist, even within the *Inquiry and the National Science Education Standards* (NRC 2000), practitioners and researchers feel free to define inquiry around their methods as they see fit (Anderson 2002). We believe the most effective method to address these nomenclature and usage discrepancies is to provide a rubric that connects the catchphrase terms of inquiry such as "guided" and "structured" to discrete levels of student independence.

Inquiry rubrics

The first rubric to receive wide recognition for characterizing inquiry in laboratory manuals was presented in Schwab (1962) and Herron (1971). The Level of Openness in the Teaching of Inquiry (Herron 1971) used the dimension of guidance to characterize the level of inquiry a laboratory exercise facilitated. Each of three characteristics (problem, ways and means, and answers) was coded as *given*, meaning that guidance was provided, or *open*, meaning that guidance was withheld. The permutation of characteristics and "levels of openness" led to four levels of inquiry, as shown in Table 1.

Based on the tools developed from Schwab and Herron's work, the Biological Science Curriculum Study (BSCS) was analyzed and another rubric was produced for assessing inquiry in K–12 laboratories (Fuhrman et al. 1978; Tamir and Lunetta 1978). Next, Germann, Haskins, and Auls (1996), in their analysis of high school laboratory manuals, developed a rubric from the works of their predecessors. However, these rubrics have been criticized for their inability to represent the cognitive and epistemological components of inquiry (Chinn and Malhotra 2002). In response, Chinn and Malhotra (2002) devised a rubric for assessing the resemblance of a laboratory exercise to the authentic science of practicing scientists.

Within the literature, there are fewer inquiry rubrics developed for use at the undergraduate level. Brown et al. (2006) proposed a continuum similar to that of the NRC (2000) and gave examples of its uses in their investigations into college science professors' conceptions of inquiry. We found that in spite of these and other attempts to quantify inquiry into discrete levels, ambiguity still prevails, as discussed above.

TABLE 1

Levels of openness in the teaching of inquiry (Schwab 1962; Herron 1971).

	Problem	Ways and means	Answers
Level 0	Given	Given	Given
Level 1	Given	Given	Open
Level 2	Given	Open	Open
Level 3	Open	Open	Open

Methods: Development of a rubric to characterize inquiry in undergraduate laboratories

From the above-mentioned review of literature, we developed a rubric to characterize the level of inquiry in undergraduate laboratory activities or exercises. Our rubric builds upon and expands the granularity of previous rubrics described above.

We collected college laboratory manuals across science disciplines for evaluation, including texts that specifically used the word "inquiry" in the title. Others were chosen based upon literature references discussing inquiry in science.

We analyzed 22 laboratory manuals and nearly 400 experiments leading to the articulation of more specific levels of inquiry and more detailed characteristics. The characteristics of the rubric originated from two sources, the terminology used in laboratory manuals to organize components of a lab and the key elements in a laboratory activity where students might become independently engaged. For each experiment or activity, we analyzed each characteristic based upon the criterion of student independence. For example, if the problem or question was given to the student, then it was coded as *provided*. If students were responsible for developing their own procedures without guidance from the lab text, then it was coded as *not provided*. In Table 2 we identify five levels of inquiry based upon six characteristics.

The characteristics

The six characteristics represent areas in the analyzed activities and experiments where students could act independently. Thus, the rubric, while not being designed as a classroom observation rubric, does make explicit the level of student independence facilitated by a given experiment. The criterion for evaluation in all cases is the level of student independence associated with each characteristic.

The "problem/question" characteristic refers to the topic of investigation in the activity. The rubric is not designed to evaluate the complexity of the question that is asked in the investigation (e.g., "Does air contain nitrogen?" versus "How does solvent affect the rate of reaction?"); rather, it focuses on student independence. The key criterion for analysis is the question "Does the student formulate the question under investigation, or does the lab text provide it?"

"Theory/background" refers to all prior knowledge necessary to the investigation. The "procedures/design" characteristic of the rubric refers to the experimental procedures students execute, while the "results analysis" characteristic specifies how data are interpreted and analyzed. "Results communication" characterizes the manner by which data and experimental results are presented—are students given options on how to communicate results, or does the manual prescribe a specific method? "Conclusions" addresses whether the manual provides a summary or list of observations and results that should have been obtained in the laboratory.

The "level" denotes the extent to which a laboratory investigation provides guidance in terms of the six characteristics. Each level denotes a specific form of inquiry that can be described as follows:

- Level 0—Confirmation: An activity where all six characteristics are provided for students. The problem, procedure, analysis, and correct interpretations of the data are immediately obvious from statements and questions in the laboratory manual. This includes activities where students simply observe or experience an unfamiliar phenomenon, or learn a particular laboratory technique.
- Level ½—Structured inquiry: The laboratory manual provides the problem, procedures, and analysis by which students can discover relationships or reach conclusions that are not already known from the manual.
- Level 1—Guided inquiry: The laboratory manual provides the problem and procedures, but the methods of analysis, communication, and conclusions are for the student to design.
- Level 2—Open inquiry: The problem and background are provided, but the procedures/design/methodology are for the student to design, as are the analysis and conclusions.
- Level 3—Authentic inquiry: The problem, procedures/design, analysis, communication, and conclusions are for the student to design.

Inter-rater reliability

To determine the robustness and reliability of our rubric, we conducted an inter-rater reliability study using three reviewers across three laboratory manuals including 36 laboratory activities. Each researcher evaluated each laboratory, then met to discuss his or her ratings. If desired, the researchers could change their ratings after discussion. The inter-rater reliability (IRR) value was found to be 83% agreement, which is above the minimal value of 70% to establish reliability.

Findings

The rubric we developed and validated can be successfully applied across multiple science disciplines to determine the level of inquiry within a

TABLE 2

A rubric to characterize inquiry in the undergraduate laboratory.

Characteristic	Level 0: Confirmation	Level ½: Structured inquiry	Level 1: Guided inquiry	Level 2: Open inquiry	Level 3: Authentic inquiry
Problem/Question	Provided	Provided	Provided	Provided	Not provided
Theory/Background	Provided	Provided	Provided	Provided	Not provided
Procedures/Design	Provided	Provided	Provided	Not provided	Not provided
Results analysis	Provided	Provided	Not provided	Not provided	Not provided
Results communication	Provided	Not provided	Not provided	Not provided	Not provided
Conclusions	Provided	Not provided	Not provided	Not provided	Not provided

More structure ⟵⟶ **Less structure**

laboratory experiment or activity. We used this rubric to analyze undergraduate laboratory manuals in astronomy, biology, chemistry, geology, physical science, physics, and meteorology, as displayed in Table 3.

We found that although many recently published laboratory manuals incorporate advances in science such as novel concepts, different instruments, and new techniques, these were not accompanied by a corresponding shift in pedagogy to incorporate inquiry. The analysis of 386 individual laboratory activities revealed that the vast majority of the experiments were highly structured Level 0 or Level ½ laboratories, as shown in Table 3. All of the geology experiments (n = 46) from three different manuals were found to be Level 0, i.e., Confirmation laboratories. In the discipline of chemistry, where we analyzed the greatest number of manuals (n = 13), the vast majority of experiments (n =191 out of 229) were classified as Level ½ —Structured Inquiry. We also identified 12 Level 0—Confirmation, and 21 Level 1—Guided Inquiry chemistry experiments. The only Level 2—Open Inquiry chemistry experiments (n = 5) we found were contained in *Inquiries Into Chemistry* (Abraham and Pavelich 1999). We note that in contrast to every other text, this laboratory manual did not provide a background section for any experiment. (Rather than removing this laboratory manual from consideration, we suspended the use of the "background" characteristic for evaluation of each laboratory.) In physics (n = 11), physical science (n = 33), meteorology, (n = 17), and astronomy (n = 13), all the laboratories were either Level 0 or ½. In biology (n = 37) inquiry-based manuals, we found 22 Level 0, 10 Level ½, and 5 Level 1 experiments. In looking at the overall set of data from these laboratory manuals, we found no laboratories that could be classified as Level 3, and relatively few were Level 2 activities.

Implications: Articulation in K–16 science education

Our findings are interesting in light of the changes in K–12 science curricula, where a concerted effort is being made to increase the amount of inquiry (Germann, Haskins, and Auls 1996; Kyle 1980). According to the 2005–2006 ACT National Curriculum Survey of over 35,000 teachers and faculty members, college faculty place less importance on science process knowledge and inquiry skills than middle school and high school teachers do (ACT 2007, Table 5.2, p. 28). Even in cases where innovative laboratory curricula such as green chemistry (see Table 3) have been developed, the new methodologies do not promote a high level of inquiry. From our analysis of undergraduate laboratory texts, it appears that the dominance of more highly structured laboratories are aligned with the values and perspectives of faculty members cited in the ACT study.

Why has so little progress been made with respect to inquiry at the postsecondary level? Certainly, college faculty perceive significant obstacles to the incorporation of inquiry into laboratories, as Brown et al. (2006) state, in part due to instructors' conceptions of inquiry and its constraints:

"However, we claim that the overriding constraint to implementing inquiry among the faculty in our sample was not the logistical, nor even the perceived student factors, but the instructor's meaning of inquiry. College science faculty in our study held a 'full and open inquiry' view (NRC 2000)… This full and open inquiry view reinforced perceived problems with inquiry teaching: that inquiry is unstructured, time consuming, and difficult to enact with 20 or 200 students" (p. 798).

Indeed, the quest to complete a laboratory in a two- or three-hour time period is a powerful driver toward a more structured curriculum and laboratory manuals that respond to that constraint.

We cautiously note that our findings do not mean that inquiry cannot exist when confirmation-oriented laboratory manuals have been adopted. Rather, we believe that it is incumbent upon faculty to adapt the experiments or activities and modify the amount of inquiry in which students are engaged. However, traditional laboratories cannot be converted into an inquiry-based activity by simply removing the instructions for completing the activity. Authors have demonstrated that instructors can modify Level 0 confirmation experiments to incorporate inquiry (Farrell, Moog, and Spencer 1999; Huber and Moore 2001; Mohrig, Hammond, and Colby 2007; Oliver-Hoyo, Allen, and Anderson 2004; Pavalich and Abraham 1977; Uno 1990). In many cases, these are classroom-by-classroom efforts accomplished where faculty are motivated to change the laboratory curriculum.

Conclusion

We have provided faculty with an expanded tool to determine the level of inquiry fostered by their laboratory curriculum. Faculty may use this rubric to evaluate a course or entire departmental program and easily compare ratings across courses. Researchers may also use this rubric as a well-defined means of communicating with each other in the literature, thereby avoiding the confusion that currently permeates the literature with varied uses of inquiry.

Ultimately, faculty control the degree to which inquiry is facilitated

TABLE 3

Evaluation of levels of inquiry for laboratory texts across science disciplines.

	Level of Inquiry						
	0	½	1	2	3	Experiments in manual	Experiments evaluated
ASTRONOMY							
PH-110 Principles of astronomy and space laboratory manual (Queensborough Community College Department of Physics 2006)	13					14	13
BIOLOGY							
Inquiry into life lab manual (Mader 2000)	22					32	22
Introductory microbiology: An inquiry-based laboratory manual (Otigbuo and Keyser 2006)		10	5			20	15
CHEMISTRY							
LASER experiments for beginners (Zare et al. 1995)	8					29	8
Cooperative chemistry laboratory manual (Cooper 2006)	2	4	9			15	15
Laboratory inquiry in chemistry (Bauer, Birk, and Sawyer 2005)	2	9	12			29	23
CHM 115 labaratory manual, fall 2006 (Purdue University Department of Chemistry 2006)		7				23	7
Working with chemistry: A laboratory inquiry program (Wink, Gislason, and Kuehn 2005)		24				26	24
Inquiries into chemistry (Abraham and Pavelich 1999)		5		5		63	10
Laboratory manual for general, organic, and biological chemistry (Timber-lake 2007)		12				42	12
Modern projects and experiments in organic chemistry: Miniscale and standard taper microscale (Mohrig et al. 2003)		13				43	13
Green organic chemistry: Strategies, tools, and laboratory experiments (Doxsee and Hutchison 2006)		19				19	19
Exploring chemistry: Laboratory experiments in general, organic, and biological chemistry (Peller 2004)		19				33	19
Organic chemistry laboratory with qualitative analysis: Standard and microscale experiments (Bell, Taber, and Clark 2001)		29				45	29
Microscale and miniscale organic chemistry laboratory experiments (Schoffstall, Gaddis, and Druelinger 2004)		42				65	42
Experiments in biochemistry: A hands-on approach (Farrell and Taylor 2006)		8				13	8
GEOLOGY							
Laboratory manual in physical geology (Busch 2006)	11					16	11
Laboratory manual for physical geology (Zumberge, Rutford, and Carter 2003)	17					29	17
Exercises in physical geology (Hamblin and Howard 2005)	18					23	18
METEOROLOGY							
Exercises for weather and climate (Carbone 2007)	17					17	17
PHYSICAL SCIENCE							
An introduction to physical science laboratory guide (Shipman and Baker 2006)		33				55	33
PHYSICS							
Physics by inquiry, vol. 1 (McDermott and the University of Washington Physics Education Group 1996)	5	6				59	11
Total	115	240	26	5	0	710	386

by how curricula are adapted and implemented in laboratory. Use of this robust rubric offers a method to critically evaluate laboratories, to make data-driven decisions at the programmatic level, and to drive changes in the curriculum to foster inquiry.

Acknowledgments

We would like to acknowledge the contributions of Jeffrey R. Raker at Purdue University to the inter-rater reliability study. This research is supported by the National Science Foundation under Grants No. 0737784 (CCLI) and No. 0536776. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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The work reported in this article makes use of this rubric to characterize the level of inquiry of two laboratory curricula and to investigate the following question: How does the degree of inquiry-based laboratory instruction impact student performance and student perseverance in the laboratory portion of a first-semester general chemistry course? Methodology In 2008, a commercially published guided-inquiry laboratory curriculum (Kerner & Lamba, 2008) was instituted for the first-semester general chemistry course at a two-year community college. This change provided a case study of the ne Keywords: science laboratory chemistry laboratory inquiry level organic chemistr. This work is licensed under a Creative Commons Attribution 4.0 International License. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.Â Learning Scientific Inquiry in the Studentsâ€™ Laboratory. In Hegarty- hazel E (ed.). The student laboratory and the science curriculum. London, Croom Helm. [22]. krajick, J., Mamlok, R. and Hug, B 2001. Modern Content and Enterprise of Science: Science education in the 20th century. [23]. Lazarowitz, R., and Tamir, P., 1994. Research on using laboratory instructions in science in Gabel D L (ed.). Hand book of research in science teaching and learning, (pp. 94-130), New-York Macmillan. [24]. Lunette, V.N., 1998. The Undergraduate Research Program (URP) at CSHL provides an opportunity for undergraduate scientists from around the world to conduct first-rate research. Students learn the scientific process, technical methods and theoretical principles, and communicate their discoveries to other scientists.Â In addition to doing research in the lab, URP participants attend a series of specially designed workshops, seminars and collegial events. Workshops focus on learning particular skills, such as Python programming, while seminars cover research topics, responsible conduct of research, and career development.