

A rubric to characterize inquiry in the undergraduate chemistry laboratory

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Abstract: Consensus does not exist among chemists as to the essential characteristics of inquiry in the undergraduate laboratory. A rubric developed for elementary and secondary science classrooms to distinguish among levels of inquiry was modified for the undergraduate chemistry laboratory. Both peer-reviewed experiments in the literature and commercially available experiments were evaluated using the rubric, revealing a diversity of uses for the word inquiry. The modified rubric provides a valid and reliable standard of measure for chemists to examine their laboratory curriculum. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 212-219.]

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Introduction

For over 30 years, chemists have debated the appropriate uses of the laboratory in the undergraduate curriculum (Fuhrman et al., 1978; Pavelich and Abraham, 1979; Tamir and Lunetta, 1981; Fuhman et al., 1982; Hofstein and Lunetta, 1982; Domin, 1999a, 1999b; Johnstone and Al-Shuaili, 2001; Garratt, 2002; Lederman, 2004; Jalil, 2006). Domin (1999b) discussed the relative merits of inductive vs. deductive laboratories and whether students should develop general principles from specific observations or vice versa. Garratt (2002) cautioned against defining chemistry as a laboratory-based science, but instead argued for the importance of ‘purposeful observations’. Jalil (2006) noted the opportunity that laboratory provides for students to make connections between theory and practice, but emphasized that such instruction should also support the cognitive development of students. Martin-Hansen (2002) claimed that the effectiveness of laboratory as a method of instruction stems from the opportunity that students are given to ask questions, form hypotheses, collect and analyze data, and draw practical conclusions that can enable them to answer their questions.

Constructivism and inquiry

Constructivism as a theory of learning posits that “*knowledge is constructed in the mind of the learner*” (Bodner, 1986). Learning occurs when the student utilizes higher order thinking skills by connecting new knowledge to prior knowledge. Constructivism advocates instructional activities that encourage student-initiated and student-directed learning. Activities that engage students in scientific inquiry facilitate their construction of knowledge.

Martin-Hansen argued (2002) that students who participate in asking questions, forming hypotheses, collecting and analyzing data, etc. are engaged in scientific inquiry. However,

many undergraduate chemistry experiments present students with directions for data collection and analysis to lead to a conclusion already known by students before even beginning the 'experiment'. Classic examples of such pre-determined outcomes would be experimentally determining the value of the ideal gas constant, or using heats of reaction to determine the stoichiometry of a reaction. What do students learn from these laboratories? Can such experiences be considered inquiry?

What are the defining characteristics of inquiry in the undergraduate chemistry laboratory? There exists no operational definition of the term. Lack of consensus has led to popularization of the term. Identifying and characterizing inquiry in undergraduate chemistry laboratory experiments requires a reliable and valid rubric* to assess the level of inquiry. Since the 1960s, education researchers across the natural sciences have developed various iterations of three distinct instruments, each one designed to assess the level of inquiry at which students are engaged during instructional activities (Schwab and Brandwein, 1962; Herron, 1971; Smith, 1971; Shulman and Tamir, 1973; Tamir, 1977; Fuhrman, 1978; Fuhrman et al., 1978; Lunetta and Tamir, 1979; Tamir and Lunetta, 1981; Fuhrman et al., 1982; Lederman, 2004).

Fuhrman (1978) developed the Laboratory Structure and Task Analysis Inventory (LAI) to analyze science curricula. The LAI contains two sections: the first examines the organization of the laboratory by the instructor, while the second identifies laboratory tasks completed by the student; each of these sections is divided into four subsections containing several categories by which the laboratory activities are assessed (Fuhrman et al., 1978). Fuhrman and colleagues (1982) used the LAI to examine laboratory activities from biology, physics, and chemistry curricula in order to determine the extent to which the laboratory materials reflected the goals of the curriculum. After examining the coherence between stated curriculum goals and the structure of materials and procedures used by students, these researchers identified a low level of inquiry and independence in the laboratory activities, concluding that students commonly worked as technicians following explicit instructions, with relatively few chances for higher-level cognitive processing (Tamir and Lunetta, 1981). Lunetta and Tamir (1979) used these findings to provide a list of twenty-four skills related to the goals of inquiry and problem-solving, affirming the importance of selecting lab activities that enhance teaching goals, and making those goals explicitly clear.

The Classroom Observation Instrument was developed by Smith (1971) as a tool to analyze inquiry in earth science curriculum. Its central focus is upon observable behaviors exhibited by both the instructor and the students throughout the laboratory, during the three phases that characterize most laboratory activities: pre-lab, the experiment, and post-lab.

The 'Levels of Openness' framework (Schwab and Brandwein, 1962; Herron, 1971; Shulman and Tamir, 1973) and Continuum of Scientific Inquiry rubric (Lederman, 2004) characterize the degree to which students have the freedom to make choices before, during, and after the laboratory experiment, as opposed to follow prescribed directions. Lederman (2004) used this four-level continuum to analyze high school science laboratories, concluding that students are rarely asked to think for themselves during experiments.

Research question

Given the validity of Lederman's Continuum of Scientific Inquiry in high school science classrooms, we wondered whether the levels would be valid for characterizing inquiry in

* We use the word 'rubric' in the following sense: A rubric comprises a set of ordered categories that frame a set of evaluation criteria. Rubrics are typically used to evaluate student work, e.g., completed assignments or laboratory reports. Rubrics can also be used to classify varying levels of attributes that a document (a laboratory exercise, a website, etc.) possesses.

undergraduate chemistry laboratories. Specifically, we sought to modify Lederman's work to characterize undergraduate chemistry laboratory experiments developed under the auspices of the Research Experiences to Enhance Learning (REEL) Project, an NSF-funded Undergraduate Research Center. The goals of the REEL project include introducing authentic lines of research into first and second year chemistry laboratory courses, with an emphasis on general chemistry, environmental chemistry, and organic chemistry. We describe below our use of Lederman's system and its reliability and validity in the undergraduate chemistry laboratory.

Methodology

Twenty-eight laboratory experiments were selected to establish the reliability of our rubric. General/environmental chemistry experiments were selected from three commercially published laboratory curricula (Abraham and Pavelich, 1999; Bauer et al., 2005; Wink et al., 2005), all of which use the word 'inquiry' in the name of their curriculum. Two of these inquiry laboratory curricula were purposefully structured by their authors so as to include some experiments with lesser degrees of inquiry (e.g., guided inquiry) and other experiments offering greater degrees of inquiry (e.g., open inquiry). Organic chemistry experiments (Senkbeil, 1999; Krishnamurty et al., 2000; Ciacco et al., 2001; Wachter-Jurcsak and Reddin, 2001; Amburgey-Peters and Haynes, 2005; Baru and Mohan, 2005; Cough and Goldman, 2005; Kjonaas and Mattingly, 2005; Nicaise et al., 2005; White and Kittredge, 2005) were selected from the *Journal of Chemical Education*, by searching on the keywords of inquiry and discovery-based learning.

Experiments selected to validate the rubric were chosen to represent a broad selection of chemistry concepts, including the same concepts (e.g., sodium borohydride reductions) across sources in order to ascertain the extent to which the rubric could distinguish between chemically similar experiments. Experiments were also selected from both of the inquiry tiers self-identified by the authors to assess the capability of the rubric to make similar distinctions.

Given the structure of REEL initiatives across teams (general chemistry/environmental chemistry, and organic chemistry), inter-rater reliability (IRR) was calculated independently for the 18 general chemistry/environmental lab experiments, again for the 10 organic experiments, and then for all 28 experiments as a whole.

The method of analysis is described as follows. Experiments were examined section-by-section: pre-lab information, procedure, and calculations/results. First, the experiment was inspected to ascertain whether an explicit problem was posed, or a question asked, about a particular phenomenon. Next, experimental procedures were scored to reflect the extent to which they were prescriptive (telling students what to do and how to do it), or the degree to which experimental procedures provided opportunities for the students to decide what actions to take. Finally, by examining the variety of questions asked in the post-lab section and making comparisons to the information provided in the pre-lab section, the laboratory experiments were judged as to what extent the students were to calculate answers and craft conclusions in echo of information provided/stated in the pre-lab in advance of the laboratory.

For example, the levels characterizing both ends of the inquiry continuum were readily recognizable by certain characteristic features:

- Level 0 – The laboratory manual began with a description of the phenomenon under study (e.g. factors that affect rate of oxidation of 'X'); an explicit method of data collection was presented with no option for alternate paths by the student; the manual

contained a set of instructions for analyzing data and/or drawing conclusions already explained in the section(s) outlining the problem.

- Level 3 – The laboratory manual directed the student to explore a general phenomenon (e.g. gases/gas laws); suggestions for lines of exploration were provided, but no specific procedures or methods of data analysis were given.

A team of three researchers evaluated each laboratory experiment twice. The researchers used the rubric to individually evaluate the experiments and subsequently met to discuss their evaluations. Each researcher evaluated the experiments again, allowing for changes if he/she desired. Finally, an inter-rater reliability (IRR) value was calculated for each experiment.

Results

Table 1 shows the results of inter-rater reliability calculations for the general/environmental experiments, for the organic chemistry experiments, and for all experiments. Of the twenty-eight experiments in the sample, one experiment was not rated using Lederman's rubric due to insufficient detail regarding instructions given to students.

The IRR for each sub-group of experiments and the collection of experiments overall is good, given the standard minimal value of 0.70 as a cut-off for establishing reliability. Based on discussions between the raters during the IRR process, we found more detailed descriptions were required than were provided in Lederman's continuum. For example, levels 2 and 3 needed a more specific description of the activities carried out by students in order to refine the characterization of that particular type of experiment. We found it important to be able to differentiate among experiments as to whether students were expected to develop procedure(s), decide what data to collect, and/or determine how the data should be interpreted in order to propose a viable solution. Table 2 presents modified descriptions of the levels found in Lederman's continuum to provide clear criteria for determining the relative levels of inquiry. Table 3 provides a visual comparison across the levels of inquiry.

Table 1. Calculation of inter-rater reliability.

	Final ratings		
	Number of experiments with agreement	Total number of experiments	Inter-rater reliability
General Chemistry / Environmental Chemistry	16	18	0.89
Organic Chemistry	7	9	0.78
Overall	23	27	0.85

Table 2. Rubric to identify level of inquiry.

Level of Inquiry	Description
Level 0	The problem, procedure, and methods to solutions are provided to the student. The student performs the experiment and verifies the results with the manual.
Level 1	The problem and procedure are provided to the student. The student interprets the data in order to propose viable solutions.
Level 2	The problem is provided to the student. The student develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.
Level 3	A 'raw' phenomenon is provided to the student. The student chooses the problem to explore, develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.

Table 3. Levels of inquiry across undergraduate chemistry laboratory experiments.

Level	Problem/Question	Procedure/Method	Solution
0	Provided to student	Provided to student	Provided to student
1	Provided to student	Provided to student	Constructed by student
2	Provided to student	Constructed by student	Constructed by student
3	Constructed by student	Constructed by student	Constructed by student

Figure 1 depicts the distribution of the twenty-seven experiments as rated across the levels of inquiry. A wide range of experiments were sampled, from those with essentially no inquiry features (Level 0) to those which require the student to define the problem of interest as well as appropriate methods of data collection and data analysis (Level 3).

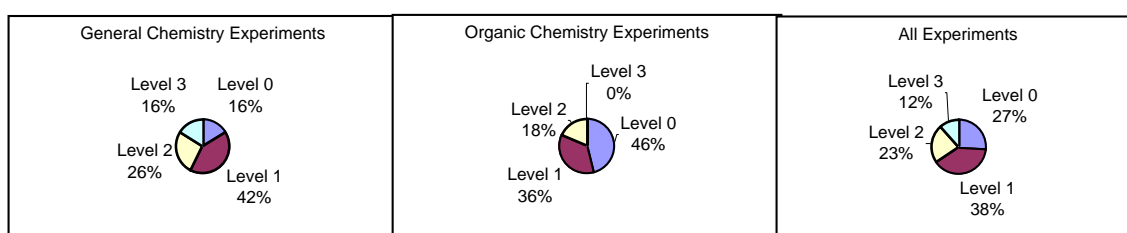
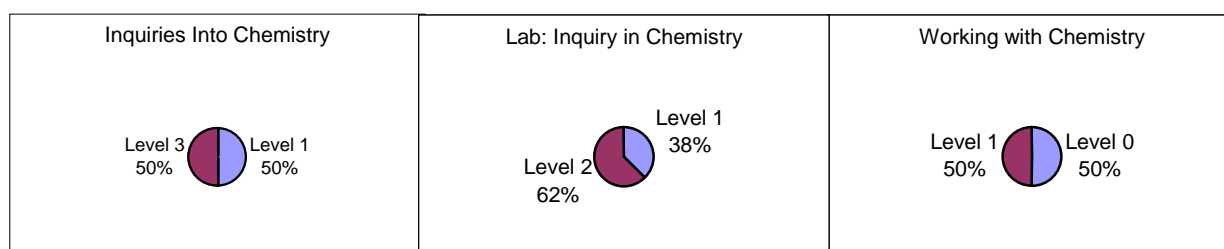
Figure 1. Distribution of experiments across levels of inquiry.

Figure 2 shows the ratings of selected experiments within the three commercially published lab manuals sampled for this research. *Inquiries into Chemistry* (Abraham and Pavelich, 1999) provides laboratory experiments characterized as either guided inquiry [“*specific instructions as to what experiments to conduct ... (student) should do work in the order indicated*” (p. 3)] or open inquiry [“*designing and carrying out (student’s) own experiments ... no detailed instructions on how to approach these systems.*” (p. 275)] Our modified rubric identified these different characterizations of inquiry as consistent with Level 1 and Level 3.

Figure 2. Ratings of commercially published inquiry laboratory programs.

Laboratory Inquiry in Chemistry (Bauer et al., 2005) describes its curriculum as one in which students assume the role of chemist and “*design their own experiments*”, (Bauer et al., 2005, p. v) adapting techniques to their specific problems. Analysis of the *Laboratory Inquiry in Chemistry* experiments placed them among both Level 1 and Level 2 using the modified inquiry rubric.

Working with Chemistry (Wink et al., 2005) structures laboratories in experiment groups, each one containing a skill-building laboratory that “*shows students how to use a technique*” (p. x) and an application laboratory in which students utilize concepts from skill-building labs for use in a given “*professional scenario which is more open in inquiry style.*” (p. x) Use of

the modified inquiry rubric to score *Working with Chemistry* laboratories showed experiments to occupy both Level 0 and Level 1.

Discussion

Lederman's continuum was originally developed for use in high school science classrooms, including, but not limited to, chemistry. Our modifications and application of the inquiry rubric to a wide spectrum of chemistry experiments support the validity of using it to characterize varying levels of inquiry in the undergraduate chemistry laboratory. The high inter-rater reliability across both general/environmental chemistry and organic chemistry classifies this rubric as robust. The findings from this research can distinguish among levels of inquiry as identified by commercially published laboratory programs.

Significance of the inquiry rubric and its potential uses

The significance of this research lies in its ability to move forward the conversation regarding the most appropriate goals and pedagogies for the undergraduate chemistry laboratory. As of late, inquiry has gained status as a 'buzzword' of sorts, with many chemists using it (sometimes somewhat indiscriminately) to describe their instructional approach to laboratory. Case in point - each of the laboratory experiments in the sample for this research was self-identified by their respective authors as 'inquiry.' And yet, our findings clearly show that not all instances of inquiry are equivalent, i.e., they do not necessarily imply or describe the same learning opportunity for students. There exist shades of inquiry with varying degrees of freedom in the student experience.

Potential uses of this inquiry rubric include the opportunity to equip chemists with a quantitative means of comparing and debating the levels of inquiry as they design curriculum and seek to improve learning for students of chemistry. Experiments that might on the surface appear to be essentially equivalent in terms of core concepts and measurements can now be compared directly to one another as to which affords more structure and which provides more inquiry for the student experience. Faculty whose instructional goal is to move students from structured laboratory experiences to increased responsibility for decision making in the laboratory can use the rubric to arrange their experiments in order of increasing levels of inquiry.

For example, consider a laboratory where students are asked to confirm that the rate of reaction increases with temperature. Students might be given a chemical system to investigate, a data table to fill out, and post laboratory questions to answer. Using the inquiry rubric this laboratory would be a Level 0, the students are simply verifying the relationship. However, the level of inquiry could be increased by stating that the students are to investigate the relationship between temperature and reaction rate. The chemical system could still be given, but the students could be asked to develop a hypothesis, data collection and analysis procedures, and viable conclusions consistent with the data that evaluate the veracity of the hypothesis. This laboratory experiment has been transformed into Level 2.

The inquiry rubric also lends itself to use in curriculum evaluation. Departments that are engaged in programmatic evaluation can use this reliable and robust rubric to characterize the current curriculum. If results from using the inquiry rubric indicate a poor fit between the declared departmental or programmatic goals and the reality of student experience, then the rubric provides a roadmap to direct meaningful data-driven change. For example, if the general chemistry laboratory curriculum is analyzed and none of the laboratories are rated as level 2 or 3, then the curriculum can be modified. Level 0 or Level 1 laboratory experiments could be replaced with Level 2 experiments that use a more open inquiry approach. Alternatively, current laboratory activities could be modified to include experiences where

the students design data collection and analysis procedures, and proposed viable solutions based upon the data.

Systematic use of the inquiry rubric to guide choices in laboratory instruction will facilitate chemists' transition from choosing laboratory experiments because they provide easy to follow directions toward choosing laboratory experiments because they provide carefully crafted opportunities for chemistry students to engage in inquiry.

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