Implementing the Science Writing Heuristic in the Chemistry Laboratory

K. A. Burke and Thomas J. Greenbowe*
Department of Chemistry and Department of Curriculum and Instruction, Iowa State University of Science and Technology, Ames, IA 50011-3111; *tgreenbo@iastate.edu

Brian M. Hand
Department of Curriculum & Instruction, University of Iowa, Iowa City, IA 52242

Over the past twenty years, educational research studies have shown that if a traditional laboratory report format is used with traditional verification activities, students may learn laboratory techniques, but they learn little else (1–3). To address this problem, inquiry and collaborative learning have been used as instructional strategies in college introductory chemistry laboratory (4–7) and organic chemistry (8–11) courses. In a guided-inquiry format, students are not told explicitly how to do the experiment; they are required to be more active in designing the experiment than with a traditional format. Students who use inquiry procedures are more likely to understand what they have done and why they have done it because they have proposed a hypothesis, designed an experiment to test this hypothesis, collected data, observed trends, and made connections between observations and principles (12–14). Guided-inquiry experiences help students think about the ideas underlying laboratory work, construct concepts to answer open ended-questions, and engage in independent thought (15–20).

Studies of the use of inquiry approaches in college science laboratory courses (21) provide evidence that these strategies:

• Are more student involved and more inductive than more traditional approaches;
• Provide less direction and therefore assign students more responsibility to determine procedural strategies;
• Encourage students to make more use of science process skills;
• Produce significantly greater educational gains than traditional laboratories;
• Appear to work equally well for college students of all ability levels, not just the very academically talented; and
• Appear to be preferred by students.

However, just because students are using an inquiry laboratory manual (cf., 22, 23) does not guarantee that students are doing inquiry or that the instructor is teaching using the inquiry process (24, 25). Herron and Nurrenbern (26) stated that, “Inquiry-oriented laboratory activities teach inquiry better than lecture/demonstration or verification lab exercises, but only if teachers are skilled in inquiry teaching methods and students are given the time and guidance required to become comfortable with the new methods and expectations” (p 1358). Our goal is to provide information about how to implement the Science Writing Heuristic (SWH), an instructional technique that combines inquiry tasks, collaborative work, and writing, while providing a structure for both students and instructors to do effective activities in the chemistry laboratory. The SWH provides a structure for creating a classroom dynamic between the instructor and the students that promotes inquiry learning and leads students to understand the concepts under investigation.

Justification for the Science Writing Heuristic

Experiencing and understanding scientific phenomena and the scientific process are goals of most science laboratory courses. To achieve these goals laboratory courses should provide an opportunity for students to “restructure information” rather than simply be involved in verifying what they have been told. Students need to actively construct science knowledge (27, 28) by being purposefully involved in posing questions, determining claims, and providing evidence. Framed around the use of inquiry tasks, activities that are designed to engage students to think about the ideas underlying laboratory work have proven to be effective (19, 29). Collaborative work and writing are two techniques that have been used to engage students to think explicitly about the ideas underlying their laboratory experiment (30, 31).

Collaborative learning has been shown to benefit students sociologically, personally, and academically (32). Research has also shown that students are more engaged with their learning goals when placed in an interactive task-oriented situation than during a “lecture” or traditional laboratory format (33). Cooper suggested that students involved in effective group collaboration work to construct or comprehend challenging concepts together (34). In a nonthreatening environment, they are able to negotiate their understanding by verbalizing their reasoning, that is, by explaining how they know what they know.

Writing is an important component of the language and learning of science (35–38); without language there is no science. However, as Langer and Applebee (39) reported, science instructors (as opposed to instructors in other subjects) have their students use writing activities focusing on factual rather than conceptual information. When a writing task is structured to promote the development of conceptual understanding rather than recalling facts, knowledge transformation can occur (40); that is, the concepts about which the student is writing are transformed into a new and more enriched version than before the writing. The act of writing becomes one of learning rather than knowledge-telling where the writer purposefully links new ideas to prior knowledge to build understanding of the concepts being studied.
A critical component of the writing process as outlined by Rivard and Straw (41) is the importance of student sharing, clarifying, and distributing knowledge among peers. Asking questions, hypothesizing, explaining, and formulating ideas during peer discussions are necessary precursors for writing. Furthermore, they found that when the techniques of student discussion and individual student writing are combined, students achieve a deeper realization of the target concept(s) and that these concepts are retained over time.

An Overview of the Science Writing Heuristic

The Science Writing Heuristic, SWH, is both an alternative format students use for their laboratory reports, and a teaching model used by the instructor to help guide the flow of activities associated with an experiment (17, 24, 42–45). A heuristic can be a guide or a method used to help individuals or people to discover or reveal something. The SWH engages students in collaborative inquiry activities, negotiation of conceptual understanding, and individual writing and reflection (39, 46–48). The SWH template encourages students to talk about, deliberate, and negotiate their understandings of chemistry. The SWH also provides a template for instructors to help students think through, and build understanding of the subject matter, rather than merely following a recipe (49, 50). Using the SWH, instructors actively guide students to help them understand what they are doing, why they are doing it, and to develop conceptual understanding.

The SWH strategy mirrors the processes of dialogue and argumentation that scientists use to construct a theory or a concept. The SWH technique is consistent with the pedagogical and philosophical view of doing inquiry learning as outlined by Spencer (14).

Components of the Science Writing Heuristic

Prelaboratory Discussion

A prelaboratory discussion among the students and the instructor highlights special safety or procedural concerns. Students need to understand the safety requirements and any laboratory techniques; therefore, safety instructions and laboratory techniques are explicitly taught. For example, during an experiment in which students determine whether a red powdery starting material is pure copper or some oxide of copper, they heat the reactant to form black copper(II) oxide. The students are cautioned to carry out the experiment in a ventilated hood space to avoid inhalation of any starting material. They are further alerted to the dangers of hot porcelain or hot iron lab ware. Specific detailed instructions for doing an experiment are not provided to students.

Students, then, gather to exchange thoughts about the laboratory exercise. During this time,

- Discuss beginning questions (as a class);
- Assign their own work groups (usually pairs or groups of four, depending on the task);
- Decide what data to gather;
- Prepare a classroom data grid to be completed by the different collaborating groups; and
- Determine among themselves which group(s) should be responsible for individual tasks—collecting original data, making replications, and so forth.

Beginning Questions

At the outset of the term, students participate in training exercises as an entire group to help them formulate beginning questions (51). These questions are researchable and must be able to be answered by doing an experiment (Table 1). Prior to arrival at the laboratory, students read preview material about the collaborative inquiry activity where a problem is posed to the students. Students are not overtly told what to do or how to do it. For example, the laboratory activity mentioned in the previous section starts with the following scenario: The label has come off the bottle of a red powder in the laboratory. Heating the red powder results in a product that is black copper(II) oxide. Is the red powder pure copper or an oxide of copper? From this scenario, students think about what aspects of this activity they would like to explore and draft one or more beginning questions that will frame their investigation. An SWH laboratory manual provides information about what materials and equipment are available to do an investigation (52–54).

At the start of the laboratory session, students write their questions on the chalkboard. The group discusses which one(s) should become the class project. This freedom of choice promotes greater student engagement and motivation (24). Once they have decided on a strategy, students divide themselves into work groups to investigate aspects of the problem(s) posed by the beginning question(s).

By having the students write their own beginning questions and then having them design their own experimental procedure to answer their question(s), they are more likely to be able to explain to the instructor or to write about what they are doing and why they are doing it. Students value beginning questions because formulating them helps students to focus on the important aspect(s) of the lab exercise as well as organize themselves to perform the lab work.

Tests and Observations

Student groups work together to draft appropriate data compilation tables on the chalkboard, then begin collecting experimental information. Students typically work in groups...
of four. The instructor moves among groups, keeping the students on task, asking guiding questions, or redirecting student inquiries to classmates. As each group generates data, the information is recorded in the class data table. This is important because each group will not likely be reproducing exactly the same procedure as their neighbors. Groups can decide to divide up the tasks, vary the ratio or quantities of materials used, or both. This requires that all students examine patterns or trends arising from the overall experiment. They may do this in their work groups or in conjunction with the entire class.

At the conclusion of a collaborative laboratory activity, students engage in a classwide discussion about what the outcome of the experiment is. Because the students have decided together which beginning question(s) to investigate and how to conduct their studies, they are comfortable talking with one another about results they have obtained. They are also eager to offer their suggestions as to why there may be anomalies in the data.

The SWH is designed to promote classroom discussion during which individual student explanations and observations are compared and confirmed or contested against the insights and support of the entire group. This is accomplished when students construct their ideas via peer discussion, argumentation, and negotiation. The instructor facilitates but does not lead the discussion.

Claims and Evidence

Students are encouraged to make explicit associations among beginning questions, observations, data, claims, and evidence as well as to be able to defend their position. When students make a claim for an investigation, they are expected to note a pattern, demonstrate a generalization, articulate a relationship, or provide an explanation that they have uncovered by their work. Such activities encourage a greater sense of ownership among the students—they are not merely following a step-by-step model to complete their weekly cookbook procedure and corresponding report. By being able to state a claim and provide rational evidence for their claim, students display scientific argumentation and reasoning skills. The knowledge being discussed is their knowledge—they are required to test their knowledge and understanding against what the expectations of the activity are. By doing an inquiry laboratory activity, students have the opportunity to reflect on the concepts that are embedded in that activity and are more likely to learn these concepts (55) than if they had simply verified a concept.

Continuing to explore the example cited earlier—converting a red copper powder to black copper(II) oxide—a student claimed, “The empirical formula for the unknown red compound does not depend on the mass of that compound used in the experiment.” The experimenter cited supporting evidence: “Class members experimented with masses of the starting compound in the range of 1,0000 to 3,0000 grams. After they reacted the compound with oxygen in the air, they determined the empirical formula for the starting compound to be the same, Cu₂O, no matter what mass of the starting compound they used.”

Students view the writing of claims and evidence as an opportunity to re-examine work in lab and what was learned. Supporting a claim with evidence assists students in sorting out the data to answer the beginning question(s). One student observed, “It helps to explain the raw data and put it into context.” Another noted, “It helps put calculations into words.” Finally another student said, “It helps you to understand when you have to put it on paper—it makes you think how to explain.”

Those students who work more quickly than others are encouraged to make claims and support them with evidence while waiting for slower groups to finish their experimental work. Ideally, all groups would make and discuss claims prior to leaving the laboratory. Ultimately, this is a function of the time remaining at the end of the laboratory session after the class discussion.

Reflections

The reflections section in the SWH format encourages students to think about how their own ideas have changed by looking back on the laboratory activity. A part of this may be accomplished in the lab room with group mates or during the postlab class discussion. Students can then complete the reflection section for the report outside of class. By completing this section on their own, students are more likely to process and understand what they have done in the laboratory.

Students’ ideas can change through the course of doing their experimental work as the students understand more about the concept they are exploring or their ideas might change at some later point in time, after thinking more about their experiences. This can be seen in the following student comments:

- “Sometimes I was ‘right on’ with what I was thinking, sometimes I did a 180.”
- “Sometimes my results did not match my predictions—I had to explain it to myself.”
- “A lot of times I started out with one goal and ended up solving more than just my first goal.”
- “When a prediction was proven wrong, I remembered that I was wrong and why.”

When students can explain what they think they know and justify their understanding, it becomes obvious that they have learned something and are not merely providing a rote reply. For example, in the copper oxide experiment, many students predict that the reactant will lose mass when heated. Some do not think the statement that “The empirical formula for the compound is the same no matter what the starting masses of the reactants are...” could possibly be supported by the data. Upon further reflection, students realize that their experiment does support the statement and is a good example of the law of constant composition.

Students believe that their reflections play a large part in their understanding. They find that reflections make it easier for them to realize whether they grasp what they do in the laboratory. Further, writing reflections helps them to make a connection to the lecture and understand the concepts behind their lab work. As one student stated, “It helps me on exams in lecture.” Finally, “Reflections helped me think about what to do differently if I would do the experiment again.”
The Science Writing Heuristic Laboratory Report

The SWH laboratory report format promotes students’ participation in laboratory work by requiring them to frame beginning questions, propose methods to address these questions, and carry out appropriate investigations. It also prompts them to share and compare their laboratory findings with their peers and with information in a textbook, on the Internet, or from other sources. The SWH laboratory report provides a format to guide student discussions, thinking, and writing via beginning questions, claims and evidence, and reflections (Table 2). A carbonless laboratory notebook with alternating white and yellow quadrille pages is used for the SWH reports (56). Although making observations in the SWH format may be similar to traditional verification work, the SWH laboratory report format requires students to make claims (draw inferences) and support the claims with evidence from experimental work. The SWH helps students think about the relationships among questions, evidence, and claims, which is much more demanding cognitive work than simply verifying that the results obtained from the experiment match the accepted value reported in the literature. The reflections part of the SWH laboratory report encourages students to think how the science activity relates to their own prior knowledge and how their understanding of that topic has changed.

An SWH laboratory report and class differ from a traditional laboratory report and class. The SWH report is written with the goal of answering a series of questions designed to help the students understand the experiment they are doing and the underlying concepts associated with the experiment. The whole class votes on which beginning questions will be explored, which experiments will be done, and how they will be done. Students negotiate what they will do and why they will do it. Through discussions with their peers about which beginning questions are worth pursuing, which optimum experimental design should be used to answer the questions, and which evidence supports the claims made on the basis of the data collected, the purpose of the time spent in the laboratory changes dramatically for both students and the instructor. The whole class is involved in sharing data and analyzing the data. Each student is responsible for his or her SWH laboratory report; however, the data and their interpretation are decided by interactions with other students and the instructor. Everyone in the class is responsible for helping their classmates gain an understanding of the concept(s) being explored by the laboratory exercise.

Because the SWH laboratory report format is new to both students and instructors, we developed a grading rubric to help students write their reports and to help instructors grade the reports. Individual laboratory reports are graded using a seven-category, 30-point grading rubric. An abbreviated version of the rubric is shown in Table 3. Students are provided a thorough verbal explanation as a part of the first

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<tr>
<th>Table 2. Comparing Student Report Formats for the Science Writing Heuristic (SWH) and the Traditional Laboratory</th>
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<td>Traditional Report Format</td>
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<tr>
<td>Title, purpose.</td>
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<td>Outline of procedure.</td>
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<td>Data and observations.</td>
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<td>Discussion.</td>
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<td>Balanced equations,</td>
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<td>calculations, and graphs.</td>
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<th>Table 3. SWH Grading Rubric for Instructors</th>
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<td>Section of Report</td>
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<tr>
<td>Beginning Question(s)</td>
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<tr>
<td>Safety Considerations</td>
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<tr>
<td>Data, Observations, Calculations, and Graphs</td>
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<tr>
<td>Evidence and Analysis</td>
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<tr>
<td>Reading, Reflection, and Post-Laboratory Questions</td>
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Note: Total of 30 points for each laboratory.
laboratory session and an extensive written explanation in their laboratory manual (54) of how the points are awarded so that they are well-informed about how detailed their reports should be. The instructor completes an individual rubric grid for each student’s report. By referring to the grid and the annotated explanation of the grading rubric, the student is aware of how well the submitted work fulfills the criteria of an acceptable SWH report and where improvements might be made.

The Role of the Instructor

The instructor’s goal is to facilitate students’ progress without dictating procedures and approaches or directly answering questions (55). Instructors encourage students to use interactive constructivist techniques (where meaning is interactively socially constructed as well as personally constructed) (57, 58) to frame their questions, hypotheses, and experimental designs. Instructors guide or coach, but do not lead. The more students are able to make decisions, the more ownership, responsibility, and accountability they feel towards the laboratory activity. They become more engaged, are more motivated, exert more effort, are more interested in the laboratory activity. The more students are able to make decisions, the more engaged, are more motivated, exert more effort, are more interested in the outcome, and consequently learn more as a result (24).

Instructors need to assist students in negotiating meaning from experimental data and observations. Collaborative intra- and intergroup discussions provide ample opportunity for socially constructing concepts or ideas by making claims (drawing inferences) and supporting them with evidence from their experimental work. The socially constructed view of claims is focused around patterns of analysis; that is, students are not just generating and constructing from their own ideas but from the ideas of entire class. Effective instructor strategies for implementation of the SWH are shown in Table 4. The instructor creates a student-centered learning environment and encourages students to assume primary responsibility for their own learning.

Assessment and Evaluation of the Science Writing Heuristic

Writing is an important component of the learning process and an important component of assessing students’ understanding of chemistry. The SWH strategies include writing exercises that expand a student’s opportunity to engage with the ideas of science, rather than perceiving science writing as note-taking, fill-in-the-blank, or factual regurgitation kinds of exercises (45). Writing-to-learn tasks require students to deal with science knowledge and the practice of science and to begin to recognize what it means to construct science knowledge and the reasoning strategies necessary to accomplish this (59–61). Students using writing-to-learn experiences gain an understanding of science and the inquiry process better than students with traditional writing experiences (48). The more students are encouraged to think, the more they take responsibility for their own learning; therefore, opportunities for writing experiences promotes greater equity among the students (48). Hohenshell found that the SWH approach guides all students to think and reason at a higher level, and this closes the gap between the high achieving and low achieving chemistry students. Students who participate in the SWH approach are better able to design an experiment to address a hypothesis compared to students who participate in a traditional cookbook laboratory activity, as measured on laboratory practical examinations tasks (24). They are better able to evaluate the guided-inquiry process they performed, as well as propose changes to the existing procedure (62).

The SWH has been effectively incorporated into various curricula (including biology, chemistry, general science, geology, physical science, and physics) from elementary through post-secondary levels (at two- and four-year institutions) (6, 12, 18, 42, 46–48, 51, 63). The two lead authors for this article have used the SWH for six semesters in a college general chemistry laboratory course for science and engineering students and for two semesters in a college general

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<th>Area</th>
<th>Less Helpful Approach</th>
<th>More Helpful Approach</th>
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<td>Beginning questions (BQs)</td>
<td>There are no BQs or the TA drafts one or more BQs for the students. There is little or no discussion about BQs.</td>
<td>Each pair of students discusses BQs from prelab. Each pair writes one BQ on the chalkboard. There is a class discussion and the BQs are combined or modified. The entire class decides which BQs and parameters to investigate.</td>
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<td>Laboratory strategies</td>
<td>TA or laboratory manual outlines exactly what mass, volume, step-by-step process, etc. to use.</td>
<td>TA suggests a range of values and students choose their own values from the range. Students create a chart to collect class data.</td>
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<td>Calculations</td>
<td>TA demonstrates each calculation.</td>
<td>TA suggests that the students talk in small groups about what they have found and asks the students what information they are trying to determine and how they will go about finding it. TA tries to get all students to a point of understanding in order to discuss their results. Student help their peers to understand how to complete their work and develop claims and support them with evidence.</td>
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<tr>
<td>Class discussion</td>
<td>TA summarizes the trends and results students have found and explains the point of the laboratory exercise.</td>
<td>Students ponder the data, analyze appropriate calculations, and talk with one another to try to make meaning of the data that have been collected and what implications the data have for their studies. They discuss trends and anomalies in data, construct concepts, answer beginning questions, make claims, and outline supporting evidence.</td>
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chemistry laboratory course for agriculture, biology, consumer family science, and exercise physiology majors.

The SWH decreases the quantity of time students spend writing their reports and the quantity of time instructors spend grading reports (63). In another study, the SWH approach was found to foster a classroom dynamic that improved student performance on chemistry lecture exams and on conceptual understanding compared to students using an inquiry laboratory manual but not doing the SWH effectively (25). Students perceive that their enhanced conceptual understanding in the laboratory leads to improved performance on lecture quizzes and examinations. Replying to an end-of-semester survey about their laboratory experiences, students cited at least four laboratory experiences that directly helped them correctly answer questions in a testing environment. Importantly, effective implementation of the SWH by both students and their instructors enabled the difference in the achievement gap between males and females to be closed. Females averaged lower scores on an ACS diagnostic test compared to males. At the end of the course, females’ average scores were similar to males on total points earned in the course and on an ACS examination (24, 25).

Summary

The Science Writing Heuristic is a structured learning tool that requires both students and instructors to be active and interactive in the laboratory experience. It is a process that blends inquiry and writing practices to assist students to better understand chemistry through laboratory activities. Rather than view laboratory activities as “cookbook” verification work, students are expected to engage in the processes of science; that is, they need to pose questions, collect and analyze data, make claims based on thought-out evidence, and defend their answers among their peers. The more that instructors can encourage this inquiry-based approach, the more involved and sophisticated the students’ writing in their laboratory reports will become. This will in turn lead to richer understanding of the chemistry concepts under study.

Literature Cited