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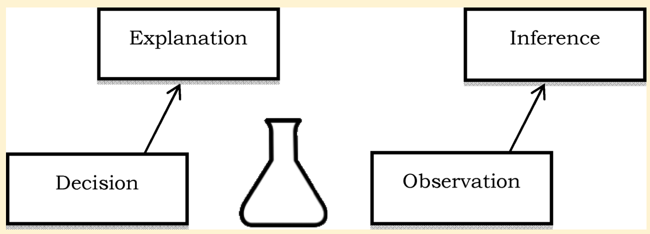
Using Self-Explanations in the Laboratory To Connect Theory and Practice: The Decision/Explanation/Observation/Inference Writing Method

Andrea Gay Van Duzor*

Department of Chemistry, Physics, and Engineering Studies, Chicago State University, SCI 309, 9501 South King Drive, Chicago, Illinois 60628, United States

Supporting Information

ABSTRACT: While many faculty seek to use student-centered, inquiry-based approaches in teaching laboratories, transitioning from traditional to inquiry instruction can be logistically challenging. This paper outlines use of a laboratory notebook and report writing-to-learn method that emphasizes student self-explanations of procedures and outcomes, specifically the Decision/Explanation/Observation/Inference (DEOI) method. The DEOI method fosters a student-centered learning environment but can be used with traditional experiments. Implementation results in organic chemistry laboratories at a highly selective, private university and a comprehensive, public university indicate the method helps a diversity of students understand laboratory procedures and encourages engagement in the laboratory as the method focuses on student ideas. Details about introducing the writing method to students, use of the method in the laboratory, and grading are included.



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INTRODUCTION

More than 25 years ago, Pickering[1] provocatively stated that while the intent of many organic chemistry teaching laboratories is to help students connect chemical theory with practice in the laboratory, the curriculum as experienced by students fails to achieve these aims (ref 1, p 143):

> *Run a dehydration of methycyclohexanol, they will say, to illustrate carbocation chemistry, an E1 mechanism, or some similar abstraction. What you illustrate in a lab is that one liquid (colorless) is turned into another (brown) and then after some work into another liquid (colorless).*

Over the ensuing years, the debate over the place of verification experiments in organic chemistry has continued.[2−5] While the chemistry education research community[6] and science standards[7] strongly promote inquiry- and discovery-based laboratories, traditional laboratories are still the norm in organic chemistry instruction, with innovation centering instead on advanced instrumentation and new content areas such as polymers.[8,9] Implementing new experiments can be difficult because instructors are unsure how to encourage students to engage with inquiry activities[10] or logistical and monetary concerns present seemingly irresolvable obstacles.[11] While some universities have approached the problem by incrementally adding inquiry experiments to verification-based courses,[12,13] an alternative means is to encourage student conceptual engagement through writing. Rather than using the laboratory report only as a means of documenting procedures and results, students can use writing to engage with, reflect on, and revise their own understandings of the chemical phenomena being investigated. Bereiter and Scardamalia[14] refer to this as "knowledge transformation" rather than simple "knowledge telling". This paper examines how use of a writing-to-learn methodology, which emphasizes explanations and inferences, scaffolds student understanding of organic laboratory procedures and investigates its utility for a course undergoing a transition from experiments with proscribed procedures to an inquiry-based laboratory environment. The similar outcomes of use of the methodology at two very different universities are discussed.

WRITING TO LEARN IN THE LABORATORY

Writing-to-learn laboratory report methodologies have been successfully implemented in college chemistry courses. Most notably, the Science Writing Heuristic (SWH), which explicitly focuses on claims and evidence,[15−17] the Model/Observe/Reflect/Explain (MORE) framework that centers on revising models of chemical phenomena,[18] and Argument-Driven Inquiry (ADI), which forefronts student construction of oral and written scientific arguments,[19−21] have all shown positive

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student learning outcomes. Additionally, SWH has been implemented in conjunction with Process-Oriented Guided Inquiry Learning (POGIL) to help connect theory and practice.[15] However, adoption of SWH, MORE, or ADI requires significant changes to laboratory curricula to include inquiry-based experiments and often multiweek investigations. An investment in professional development is often necessary for the adoption to be successful.[16] While most faculty are aware of pedagogies advocated by discipline-based research and want to implement more of these pedagogies in their classrooms, they often maintain traditional teaching because of time constraints for learning about the pedagogies and preparing new course materials.[22] With limits of time, resources, and professional development, these types of large-scale reforms may be difficult to achieve and, in many cases, can seem overwhelming to implement.

The Decision/Explanation/Observation/Inference (DEOI) method was developed as a means to incorporate the benefits of student-centered, writing-to-learn methodologies into courses that use experiments with proscribed procedures as an initial step to inquiry instruction requiring considerably fewer resources.[23] Students' laboratory note taking and report writing are expanded from the traditional "procedures" and "observations" to four columns in the DEOI method: Decision, Explanation, Observation, and Inference. As an initial step, it can serve as a precursor to some of the larger-scale instructional revisions such as SWH, MORE, and ADI.

Procedural steps are listed in the "decision" column. The column is named "decision" rather than "procedure" to emphasize that the student is actively conducting the experiment and that the procedural steps may need to change on the basis of outcomes in the lab. In the "explanation" column, students write the reasons for experimental design and procedural protocols and discuss what should be occurring at a molecular level. In the "explanation" column, students explain the procedure and explicitly connect theory and practice in the laboratory. In the "observation" column, students write their measurements, spectral data, and observables in the lab such as smells and colors. The "observation" column is the same as in a traditional laboratory notebook. In the "inference" column, students write their interpretation of observations, justify how they know what is occurring in the reaction or technique, and plan future courses of action. Observations are separated from inferences as students often have difficulty differentiating between evidence and claims.[24] Self-explanation protocols, both oral[25] and written,[26] have been found to foster conceptual understanding of scientific texts, and oral protocols have been used during experiments to improve understanding of laboratory procedures.[27] When using the DEOI method, students do not practice writing traditional laboratory reports as researchers have found that traditional laboratory reports are often not as educational as instructors hope because students become focused on parroting instructor styles and knowledge claims.[28,29] The DEOI method mirrors the type of thinking that chemists do in the laboratory even if it does not mimic the exact writing styles professional chemists use to disseminate results.

At the beginning of the semester, students are given an example of completed DEOI columns, without any instructor prompts (see Figure 1). The full handout given to students, which includes examples as well as a discussion of why the DEOI method is being used in the course, can be found in the Supporting Information.

<table>
<tr><th>Decision</th><th>Explanation</th><th>Observation</th><th>Inference</th></tr>
<tr>
<td>Mixed Melting Point

Compare unknown with trans-cinnamic acid "t-ca" (lit mp: 133°C) and 2,5-dimethylbenzoic acid "dmba" (lit mp: 132°C).

Take mp of unknown, t-ca, and dmba individually. Take mp of a mixture of unknown and t-ca and a mixture of unknown and dmba.

(lit mp from Aldrich)</td>
<td>My unknown is an acid with a mp of about 132°C. On list of unknowns the only two that are both acids and have melting points in the same range are trans-cinnamic acid and 2,5-dimethylbenzoic acid. Use mixed melting point to try to rule out one as compound identity. If the compounds in the mixture are different, the mp will usually be depressed and broadened due to colligative properties.</td>
<td>Unknown: white and powdery.
t-ca: white needle like crystals
dmba: white and powdery
<table><tr><th></th><th>mp°C</th></tr><tr><td>Unknown</td><td>131-133</td></tr><tr><td>t-ca</td><td>133-134</td></tr><tr><td>dmba</td><td>130-132</td></tr><tr><td>unk+t-ca</td><td>131-134</td></tr><tr><td>unk+dmba</td><td>97-121</td></tr></table></td>
<td>Although the unknown looks more like "dmba" it can not be since the mixed mp was broadened and depressed. The unknown may be "t-ca".

Maybe should compare IR spectra?</td>
</tr>
</table>

Figure 1. Example of a completed DEOI template for a mixed melting point experiment given to students at the beginning of the experiment. The example highlights the type of reasoning students should use when utilizing the DEOI method. The complete handout given to students explaining the DEOI method can be found in the Supporting Information.

■ IMPLEMENTING THE WRITING METHOD

The evidence presented in this paper shows that the DEOI method has been successfully used at two very different universities. It was originally introduced at a most selective, ethnically diverse, private, research university (which will be termed IvyU to follow IRB protocols) that was committed to a series of organic laboratories using an in-house laboratory manual.[23] While students did need to determine simple unknowns (for instance, the analgesics in an unknown medicine mixture by thin layer chromatography), detailed procedures were given and there was always a single, correct answer. IvyU has a one-semester intensive organic chemistry laboratory course that is not associated with a lecture course. The DEOI method has since been used for several years at Chicago State University (CSU), which is a less selective, predominately African-American, public, comprehensive university. (IRB protocols were also followed at CSU.) CSU currently uses problem-based experiments from a commercially available laboratory manual[30] and teaches a two-semester organic chemistry laboratory course sequence associated with the lecture course. The experiments in the first semester have detailed procedures and use simple unknowns to primarily teach techniques. In the second-semester experiments, the manual still typically gives detailed procedures; however, the answers are more complex, centering on structure and mechanisms. Students are advised to take the lecture and laboratory portions of the course concurrently. At the time of implementation of the DEOI method, instructors at IvyU and CSU were not ready to undertake the large-scale reform needed to switch to an inquiry-based curriculum, so a middle path was chosen to begin introducing student-centered practices.

At CSU, the laboratory instructor provides the students with a prelab template, which they can download from our course learning management system. The instructor breaks the procedure into steps in the "decision" column. Prompts are included in the "explanation", "observation", and "inference" columns of the first three laboratory templates to familiarize students with the expectations of the DEOI method. Explanation prompts are questions, such as "Why add $NaSO_3$?" or "Why take a mixed melting point?", that are intended to act as scaffolds to cue students to the types of

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explanations chemists consider in the laboratory.[31] (See the Supporting Information for an example of a prompted template.) After the first three experiments, students are still provided with the procedure in the "decision" column of the template, but the other three columns are "unprompted" and blank with no guiding questions. The prelab template also includes questions about the purpose of the lab, the reaction scheme (if applicable), a table of reagents, and pertinent safety information. Before coming to the lab, students must complete the "explanation" column and prelab questions. At CSU, students usually download the template and type in their "explanation" column ideas. They then bring in two copies: one that is given to the instructor for grading and one that they keep in a binder and on which they write their experimental observations. The "explanation" column is graded for reasoning and effort, although not necessarily chemically correct answers in the prelab. If it is important to the instructor that students keep all of their laboratory data in a bound laboratory notebook, as indeed was the case at IvyU, students can write the "decision" and "explanation" columns in their bound notebooks. However, from interviews at IvyU, students find copying the procedures into their notebooks and then retyping them again into their reports to be nonthinking busywork, which is why we have moved away from this at CSU.

During the lab, students complete the "observation" column and make changes in the "decision" column to reflect the work they actually did versus the work they planned to do. Working with their laboratory partners and asking questions of their instructor, students also begin revising the "explanation" column and completing the "inference" column. Instructors at IvyU and CSU have noted that students seem to ask more questions using the DEOI method because they need to know not just what to do next but why they are doing it. Furthermore, one instructor at CSU commented that students seem to write more observations that reflect the types of observations organic chemists find relevant than in prior semesters because the prompts helped teach the students what is important to observe.

For the laboratory report, students turn in a DEOI template with all four columns completed. The "decision" column should be finished by the end of the lab and list what they actually did in the experiment. The "explanation" column is revised to reflect new understanding gained from conducting the experiments. Students should directly record their observations from the lab without revision in the "observation" column, and the "inference" column should reflect inferences from individual observations as well as a general conclusion for the experiment. With the revised DEOI template, students also complete a few postlab questions that focus on understanding the reaction mechanisms and some real-world connections. A description of DEOI report grading at CSU is included in the Supporting Information.

■ STUDENT EXPERIENCES USING THE WRITING METHOD

The impact of the DEOI method was investigated using action research.[32,33] In action research, an instructor first determines a problem. In this case, it was observed that students who (using Pickerings's quote[1] as an example) had "good hands" and could dehydrate methylcylohexanol with high yield and purity and had good theoretical knowledge, drawing an E1 mechanism easily, could rarely state what was in their flask in the midst of a reaction. The DEOI method was created to ameliorate the problem because students must explicitly state the reason for each procedure and the meaning of observations. Action research is cyclical,[32,33] and successive cycles of implementation and evaluation have been used to improve the DEOI method and provide a better solution to the problem. At both institutions, evaluation was conducted using the 3Rs of action research:[33] *experiencing* by the author serving as a participant-observer[34] in the classroom writing field notes when observing and reflections when teaching, *examining* by analyzing student laboratory reports, and *enquiring* by conducting student and instructor semistructured interviews.[35] Emergent themes regarding students' perception of the DOEI method and their ability to link theory and practices were coded from the IvyU data[23] using constant-comparative methods between data sources.[36] These codes were then applied to the CSU data. Additionally, to better understand how students were using the method recursively to improve their understanding, prelab and report "explanation" columns were coded in a cycle of evaluation at CSU for change in ideas, depth of reasoning, and correctness. Logistical limitations at both institutions did not allow for a comparison of experimental and control classes or post-tests, as they are not part of the curriculum. Qualitative examples given in this paper are indicative of the codes derived in the action research process through triangulation of data obtained through experiencing, examining, and enquiring.

Students' experience of the DEOI method has been overwhelmingly positive, with very similar results at IvyU and CSU. A common refrain for students was that thinking about what they were doing in the lab was a new and beneficial experience. A CSU student explained:

> *Like before in my other laboratories, I just did it, wrote down my stuff that I did, but I never really processed it. You know what I mean, like when you write the questions "why do you do this?" and "why did you do that?" I think that made you sit there and think "man, why did we do this" or "why don't we add this at this time". So I think it makes you really think about what you are doing and understand it better.*

This is almost identical to an IvyU student's statement:

> *Just I think it is very good to try and actually explain every step because it makes you understand what you are doing. So it makes you, like instead of like mechanistically adding stuff and being clueless about why, it makes you think ... it definitely forced you because otherwise I do not think I would. (laughs)*

Furthermore, the prompts in the first three experiments are important for setting expectations and have students engage with the method. Another CSU student stated:

> *I liked the leading questions [prompts] ... based on the procedure and then we would know kind of what's important and what to look for. And then the more we did that ... we were able to come up with those questions on our own. And that really, that helped me connect what was going on instead of just following the recipe.*

As noted previously, question prompts are provided for only the first three experiments. Routinely, approximately one-third to one-half of the students in the laboratory will independently start using the format of the prompts in the experiments with unprompted templates, writing and answering their own questions in the "explanation", "observation", and "inference" columns. The remainder of the students still complete the

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DEOI template, but they internalize the questions rather than explicitly writing them. A more detailed examination of how students revised their explanations at CSU and how they used the method to connect theory and practice in the laboratory can be found in the Supporting Information.

As mentioned previously, instructors at both institutions have appreciated that students ask more questions in the laboratory and make observations more consistent with what chemists consider important as a result of DEOI. The nature of the DEOI format with explanations required for every procedural step also makes it more difficult for students to use the Internet to write their report because it does not follow standard report format, which unfortunately seems to often be the case when using well-known experiments. Another benefit of the DEOI method is that the focus on explanation of procedures allows instructors to clearly see what techniques students are having difficulty understanding conceptually. For instance, review of laboratory reports shows that students still struggle with understanding the seemingly simple technique of recrystallization even when they can successfully recrystallize products in the lab.

Figure 2 gives an example from one CSU student's report. In this experiment, students prepare camphor by oxidizing

Decision	Explanation	Observation	Inference
Step 4. When the reaction period is over, let the mixture cool to room temperature. Test it with starch-iodide paper, and if the test is positive, add enough saturated sodium bisulfate solution dropwise to give a negative test.	What does bisulfate do? It is a reducing agent that can destroy any excess HOCl that remains after the reaction is over. Why use sodium bisulfate to get rid of HOCl? We cannot dispose of HOCl ourselves because it will react violently with the other solutions in the waste jar.	What do you see? We tested the mixture with starch paper and it turned purple. After adding sodium bisulfate and swirling the mixture the starch paper turned clear.	There is no HOCl present in the solution.

Figure 2. Excerpt from a student DEOI report on preparing camphor from isoborneol that provides an example of how students use the DEOI method in practice. While the instructor provided the text in the "decision" column, the student self-generated the question prompts in the other columns. Her complete report can be found in the Supporting Information.

isoborneol. The oxidizing agent, hypochlorous acid, is prepared *in situ* from acetic acid and sodium hypochlorite. In this step, students are testing their reaction mixture with starch−iodide paper at the conclusion of the reaction to test if sodium hypochlorite is still present. The instructor provided text in the "decision" column, while the student wrote the "explanation", "observation", and "inference" columns, including her self-generated question prompts.

While the use of a starch−iodide paper test may on the surface seem unimportant to the experiment, it is important because it indicates students trying to understand their actions in the laboratory. Large ideas, such as the oxidation mechanism, can be learned in the lecture with little connection to the physical reality of the laboratory. Evidence of understanding the seemingly less crucial procedural steps implies students are thinking in the laboratory and trying to connect theory and practice. This student's full lab report can be viewed in the Supporting Information. While not all of her ideas are chemically correct, they do show that she is using chemical concepts to try to understand her work in the laboratory.

Successful use of the DEOI method at IvyU and CSU suggests that it is well suited for traditional experiments with set procedures. Theoretically, the DEOI method could be used with verification, simple unknown, problem solving, or inquiry experiments. However, analysis of student lab reports and discussion with students indicate it may be less effective with more challenging problem-based laboratories. Students may have lost sight of the problem solving "forest" as they strove to understand the experimental step "trees". This is described in more detail in the Supporting Information. Alternatively, it is possible that students struggled with the more complex problem solving laboratories simply because they were more complex. Future action research cycles of the DEOI method should evaluate use of the method with more challenging problem-based and inquiry experiments.

CONCLUSIONS

The intent of the DEOI method is to encourage connections between theory and practice in the laboratory by requiring students to consider the chemical reasons for procedural actions in the "explanation" column and to interpret data and draw conclusions in the "inference" column. The DEOI method has been used successfully at two very different institutions, IvyU, a highly select, ethnically diverse, private, research school, and CSU, a less-select, majority African-American, public, comprehensive school. Historically, researchers who investigate STEM learning of students at urban institutions have used "deficit thinking", citing deficiencies in student knowledge as well as cultural deficiencies, and have focused on addressing these in the classroom.[37] An unfortunate response has been to use simplified and highly structured activities with students labeled "underperforming".[38,39] Conversely, study of writing-to-learn methodologies in a single tertiary institution has shown them to be effective for diverse students.[20] The similarities in coding of student experience using the DEOI method at IvyU and CSU suggest that student-centered, writing-to-learn methodologies are highly appropriate for a wide range of students regardless of background and prior educational achievement and that the DEOI method can be successfully implemented in very different institutions. Deficit thinking is not warranted, and minority students may bring cultural resources to the classroom, such as an openness to student-centered learning and community building, which can aid in curricular reform.[40]

As the DEOI method brings student voice to experiments with clearly delineated procedures, it can be an excellent way to begin the transition to student-centered laboratories. Use of the DEOI method does not require a change in curriculum and requires relatively little instructor time to create the initial templates. When inquiry experiments have been introduced incrementally into an otherwise traditional laboratory course,[12,13] the tenor of the course remains traditional with the exception of the added inquiry experiment, which can engender a disconnect in teaching and learning expectations throughout the semester. Use of the DEOI method impacts the discourse of the entire course for students and instructors by emphasizing student explanations. The DEOI method may serve as an effective step on the path toward larger-scale inquiry curricula as students have repeatedly indicated that using the method impacts how they approach the laboratory in general because of the focus on understanding their own actions in the laboratory. Indeed, using the DEOI method at CSU has helped convince faculty of the need for increased student self-

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explanation and led in part to the implementation of the ADI curriculum[21] in the general chemistry laboratory course sequence, which required extensive course changes and faculty effort. DEOI was a fruitful first step at CSU to facilitate faculty buy-in and provided a strong foundation to allow the department to move to adopting the ADI curriculum.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00093.

Handout given to students, excerpted in Figure 1, that describes not only how to use the writing method but also why it is being used in the course (PDF and DOC)

An example of a prompted template (prompted templates are typically given for the first three laboratory experiments) (PDF and DOC)

An outline of how the DEOI prelab and laboratory reports are graded (PDF)

A more detailed account of analysis of student explanations using the DEOI method (PDF)

Full example of a student report using the DEOI method, which was excerpted in Figure 2 (PDF and DOC)

■ AUTHOR INFORMATION

Corresponding Author

*E-mal: andrea.vanduzor@csu.edu.

Notes

The author declares no competing financial interest.

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