Implementing POGIL in the lecture and the Science Writing Heuristic in the laboratory—student perceptions and performance in undergraduate organic chemistry

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This study investigated the possible connection between effective laboratory activities and student performance on lecture exams. In a traditional undergraduate organic chemistry course for non-science majors, students could predict the products of organic reactions, but struggled to provide reaction mechanisms for those same reactions, despite obtaining perfect scores on their laboratory reports where reaction mechanisms were required. In addition, student attitudes toward chemistry in general were sharply negative after taking organic chemistry. To address these two issues, we implemented POGIL activities in the course and the Science Writing Heuristic in the laboratory to replace the standard lecture format and verification laboratory experiments. This paper will focus on student performance on nucleophilic substitution reaction mechanisms on a class exam. Performance on these questions improved compared with students in past traditional classes. In addition, students were given a pre-class and post-class survey regarding their perceptions of the course. At the conclusion of the term, many students thought the class was easier than what they initially expected. This illustrates the view that non-science majors have the ability to learn organic chemistry from a mechanistic point of view, and integrate concepts learned in the laboratory with concepts presented in the lecture.

Keywords: laboratory instruction, guided-inquiry instruction, POGIL activities, Science Writing Heuristic (SWH) laboratory format, active learning, cooperative learning, learning cycle

Introduction

The science laboratory has been viewed as a critical component of the learning process (Lloyd, 1992). Over the years, a number of reviews have been published on the effectiveness of the general chemistry laboratory (Hofstein and Lunetta, 1982, 2004; Lazarowitz and Tamir, 1994; Lunetta, 1998; Tobin, 1990). These reviews indicate that a lack of evidence exists to support the idea that traditional laboratories are effective in promoting meaningful learning. Hawkes (2004) suggested, *"Duplicating what we chemists do in our laboratories (or what chemists of earlier generations used to do) does not enhance students' understanding of chemistry, but makes chemistry an irrelevance"*. This leads the traditional laboratory format to be summarized as a cookbook or verification approach that does little to help students learn concepts (Bodner *et al.*, 1998).

The organic chemistry laboratory has been criticized for the same general reasons that the general chemistry laboratory has been. Baru and Mohan (2005) have argued for the incorporation of an element of discovery in laboratory activities to ensure that student interest and enthusiasm are retained. Cooley (1991) emphasized that laboratory work should focus more on getting students to obtain and interpret data rather than making representative compounds and learning techniques. He argued, *"When they (the students) are given an explanation of what the data mean, they accept such interpretations without question and complete the laboratory with minimal effort or ability to interpret data"* (p. 503). Mohrig (2004, p. 1083) argues from a practical standpoint that since the traditional laboratory lacks evidence of producing meaningful learning, *"wouldn't it be just as effective to tell the students what they would see, without mounting expensive and time-consuming labs?"* A growing number of researchers have been calling for reform in the science education laboratory (Venkatachelam and Rudolph, 1974; McComas, 2005; Truax, 2007). The cookbook nature of the traditional laboratory fosters what Cutler describes as a *"creeping passivity"* (2007), a reference to students who are not engaged in the laboratory or in the classroom. Disengaged students begin to look at laboratory work as something they just have to show up to complete, and they can quickly lose any prior interest they may have had. This leads to students oftentimes failing to see how the experiment is relevant to them (Reid and Shaw, 2007). This is especially true in a laboratory course offered to those students who are not majoring in chemistry (Singh, 1999; Kelley and Gaither, 2001; Weidenhamer, 2007). Many students fail to see why they have to take the course, often looking at it as nothing more than a requirement. As Pungente and Badger (2003,

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Table 1 Laboratory report format comparison

Traditional laboratory report	The Science Writing Heuristic report
Title and purpose	Beginning questions
Procedure	Safety considerations
Data and observations	Tests and procedures
Balanced equations, calculations, graphs	Data and observations
Discussion	Claims
Conclusion	Evidence
	Reading and reflection

p. 779) have noted, *"organic chemistry is viewed by some students as little more than a rite of passage, or the academic equivalent of hazing"*.

Domin (1998) and, more recently, Horowitz (2007) have reviewed several efforts to reform the laboratory, including discovery-based experiments, inquiry-driven experiments, project-based learning, and collaborative learning activities. While each of these has been shown to improve student performance on exams about content as well as student attitudes, the complexities involved in organic procedures and the knowledge students bring into the course certainly plays a role in the ultimate success of these efforts. The incorporation of research-based laboratory experiments has also shown success (Gilbert *et al.*, 2002; Newton *et al.*, 2006). While these experiments would certainly arouse student interest, they can be time-consuming when students do not have the knowledge or the experience to be ready to complete them.

An alternative to the traditional approach in the laboratory is the Science Writing Heuristic (SWH) laboratory report format. This format is based on the theoretical framework of a learning cycle whereby students explore concepts to look for trends or patterns rather than verify an expected outcome (Lawson *et al.*, 1989; Keys *et al.* 1999). The learning cycle consists of three phases: exploration, term introduction, and concept application (Lawson, 2001). The exploration phase should raise questions, complexities, or contradictions. The SWH format incorporates this phase by providing students with an experiment with no direct answers, but rather many possibilities based on previous concepts covered. As the experiment is being completed, students record their data on the blackboard. These data serve as the class data, and allow students to look for trends or patterns. This allows for the introduction of new terms and concepts based on the data generated. Once the trend or pattern is found, the instructor can progress into the concept application phase. By using the data obtained during the experiment, students can use the trends or patterns found to make conclusions about examples in different contexts.

In the traditional laboratory format, the opposite is true; students follow a given set of procedures to verify a fact or synthesize a compound. In this setting, if students obtain what they are supposed to obtain, writing up the laboratory report requires little difficulty, as the explanations and answers are provided. With the possibility of only verifying one correct answer, students are not forced to reconcile their results if these results do not agree with what they were supposed to obtain (Pickering, 1985). When this happens, students can become frustrated and oftentimes write in their laboratory reports that they had faulty equipment or some forms of human error were present (Rudd *et al.*, 2002).

Table 1 shows how the SWH laboratory report format differs from the traditional format. In a traditional laboratory report, students start with the title of the experiment (The Preparation of…) and the intended purpose (to make a certain compound; to 'do' a specific reaction), both of which are supplied in advance. To follow the learning cycle approach, the SWH format replaces the purpose with beginning questions (exploration). These questions are student-generated and can only be answered by completing an experiment. The intention is that as a class, students decide what they are trying to investigate rather than having the purpose overtly given. Other major differences between the two formats are the claims, evidence, and reading and reflection components of the SWH format. After completing an experiment and collecting the appropriate data, students can answer their beginning question as a claim (term introduction). The support for this claim is evidence and can consist of spectral data, data generated by other groups, or any trends or patterns found in the class data table. The reading and reflection component allows students to ask themselves whether their results made sense. By asking this question, they can compare what happened during the experiment to what is or was covered in the lecture. Students are also required to do a small amount of research online to see whether they can apply what they did in the laboratory to some topic more relevant to them (concept application).

We have reported that in the general chemistry laboratory students spend less time writing laboratory reports and teaching assistants spend less time grading them when using the SWH laboratory report format (Rudd *et al.*, 2001). In addition, students who used the SWH format performed significantly higher on an ACS standardized examination, as well as on in-class lecture exams and quizzes (Burke *et al.*, 2006; Poock *et al.*, 2007). It has also been reported that middle- and high-school students who used the SWH format in biology have scored higher on multiple-choice and conceptual questions (Hand *et al.*, 2004; Hohenshell and Hand, 2006). Other researchers have reported similar findings after implementing this method in a variety of courses across all grade levels (Gravelle, 2006; Hand, 2007; Sarquis, 2007).

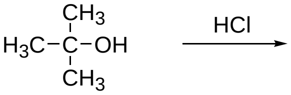
Background

In our initial pilot study, we tracked students who had previously used the SWH laboratory format in general chemistry to see whether the success they had would continue in organic chemistry. For that study, the SWH students were matched with another group of students who had just completed a general chemistry course in which the traditional laboratory report format was implemented. Analysis of the in-class exams revealed that the group of students who had prior experience with the SWH report

Draw the structure of the product formed in the following reaction:

$CH_3CH_2C(CH_3)_2OH \xrightarrow{HCl}$

Draw the mechanism for the following reaction:



$$H_3C-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{C}}-OH \xrightarrow{HCl}$$

Fig.1 Nucleophilic substitution questions on an exam

format outperformed the traditional students, even though the traditional format was implemented in the organic chemistry laboratory (Schroeder, 2007). In a subsequent study, we focused on student performance on more challenging exam questions, such as sketching reaction mechanisms and completing synthetic sequences or retrosynthetic analyses. In the traditional organic chemistry course we found that all students performed well when predicting reaction products, but when asked to provide a mechanism to show how that same reaction worked, the number of correct responses dropped by over 90%.

The focus of this work is on the concept of nucleophilic substitution. In the traditional organic chemistry course, students completed a laboratory experiment in which they reacted a tertiary alcohol (*tert*-butyl alcohol) with concentrated hydrochloric acid (Clague, 2006). The goals of the experiment were for students to get exposed to an S_N1 reaction, develop the ability to tell the difference between an S_N1 and an S_N2 reaction, and learn the trend for carbocation stability. This experiment took place two weeks prior to an exam that asked questions specifically dealing with this concept. Two types of questions on the exam should be noted; first, predicting the product of a reaction given reaction conditions, and second, writing out the mechanism for a similar reaction (Figure 1).

During a spring semester (in sequence), 90 out of the 111 people (81%) attempting the first problem received full credit. However, when the same students were asked to sketch the mechanism in the second question, a total of twenty-eight people attempted it, of whom seven did so correctly. What this shows is that even though students could recognize reaction conditions and write the correct product, they did not understand how the product is formed. Interestingly, on the laboratory report for nucleophilic substitution, thirty-two students received a perfect score, which according to the grading rubric includes a complete detailed mechanism showing *tert*-butyl alcohol reacting with HCl to form *tert*-butyl chloride. But only five people from this group receiving perfect laboratory report scores attempted this mechanism on the exam, three of whom were correct. Perhaps these students could not remember writing the mechanism in their laboratory report or never learned it in the first place. Since the mechanism was given in the laboratory manual, it could be reasonable to assume the latter.

This work focused on the same course offered during the subsequent summer term, at which point the authors were assigned as co-instructors. In contrast to the traditional format this course had used before, we implemented the Science Writing Heuristic in the laboratory and also updated the lecture portion of the course to allow for the implementation of some POGIL (Process-Oriented Guided Inquiry Learning) activities based on the model presented by Minderhout and Loertsher (2007). The effectiveness of POGIL in general and organic chemistry has previously been described, having been shown to not only increase student performance, but also decrease the number of students who withdraw from the course (Farrell *et al*., 1999; Spencer, 1999; Straumanis, 2004). Implementation of both POGIL in the lecture and the SWH in the laboratory, we believed, would help our students understand more of the difficult concepts mentioned above.

Methods and materials

The introductory organic chemistry course met every day for one hour during 8 weeks of the summer session. The corresponding laboratory met for two 3-hour sections per week. The enrollment was twenty-four. The required textbook for the lecture was *Essential organic chemistry* (Bruice, 2006) but other books (Hart et al, 1998; McMurry, 2000; Smith, 2006) were used in conjunction with Straumanis' *Organic chemistry: a guided inquiry* to supplement the POGIL activities. For the laboratory, we converted the previous traditional laboratory manual into an inquiry-based laboratory manual implementing the SWH laboratory format (Schroeder *et al*., 2006). Data were collected for quantitative analysis by photocopying student exams and recording performance on targeted questions. The performance for the summer group of students was compared to the performance of the traditional group mentioned above who took the course the spring semester that same year. For a qualitative analysis, a survey was given at the beginning of the course to gauge student perceptions of the format, and what their expectations were for the course. An evaluation was given at the end of the course to see whether student perceptions had been changed as a result of the course.

The lecture was divided into three 20-minute blocks (Table 2). During the first block, students gathered into groups and began working on the activities collectively. Oftentimes, students completed an experiment dealing with material they had not yet seen in the lecture, which allowed the instructors to frame the new activity as an extension of previously completed laboratory work. This served the dual purpose of giving the instructors an idea of what the students were able to learn from the experiment, as well as giving the students a sense of continuity between the laboratory and the lecture. During the second block, the instructors would check with each individual group to see what progress was being made. Students were encouraged to ask other groups questions before they would come to the instructors for help. When problems were encountered on specific concepts, other groups would offer insight into how

Table 2 Block style arrangement for the lecture

1st block	Hand out activity covering new material. Give a brief introduction over what was done before and how this new activity was going to try to build on previous knowledge.
2nd block	Allow the students to work collectively in groups. Walk around and visit each group to see what kind of progress is being made, and if any major difficulties are being found. Help students by acting as a facilitator instead of the source of all answers.
3rd block	Gather the class as a whole and discuss some of the concepts being addressed in the activity. Go over common misconceptions or difficulties experienced by all groups. All groups take part in the discussion.

they approached these problems. This transformed the traditional classroom into the students' own scientific community. During the final block, the instructors facilitated a discussion in which the groups of students had the opportunity to discuss how they had arrived at their solutions to the problems presented in the activity. It is important to note that the instructors needed to guide the discussion in this format; otherwise it might have been difficult to keep progressing. A new activity was given to the students every other lecture on average.

The laboratory operated in a similar manner to the lecture. All answers and explicit details were removed, instead being replaced with suggested variations. To help create a sense of community, students were encouraged to work together, put a class data table on the board, and draw conclusions based on the data that were collected and compiled. Prior to an experiment, everyone would meet in the pre-laboratory room. Students were asked whether they had beginning questions that could be answered by doing the experiment. With no products given in the manual, many questions focused on what the product would be, but in all cases a second, more productive question would surface (*i.e.* will the product be different if the acid is used as a catalyst or in equal amounts?). After students agreed upon at least two questions to study, the teaching assistants would go over the experiment, guiding students how they could proceed in the laboratory to be able to answer their beginning questions. A quiz was given after this introduction to ensure that students would come to the laboratory prepared; this allowed the pre-laboratory to be more effective and more discussion-based.

Once in the laboratory, the teaching assistants would visit each group at different stages of the experiment to see whether any difficulties or questions were arising. Students were encouraged to ask questions from other groups before asking the teaching assistants. At the conclusion of the laboratory period, students gathered around the blackboard to analyze collectively the class data obtained. The teaching assistants would serve as facilitators, asking questions of different groups. This allowed the groups of students, and not the teaching assistants, to bear the responsibility of explaining their data to the rest of the class. When a consensus emerged, students were able to make claims that would answer their beginning questions. With all groups reporting their findings, students would use the class data as evidence to support their claim. Putting all of this information together during the laboratory period ensured that everybody had most of the laboratory report written before they left. The only task students needed to complete on their own outside of the laboratory was often the reading and reflection component.

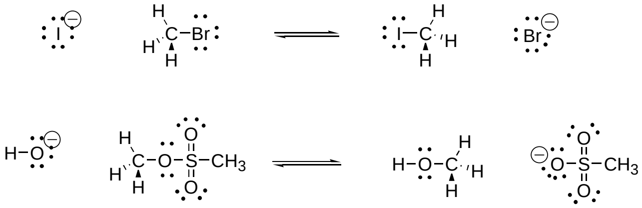


Fig. 2 One-step nucleophilic substitution model.

Experimental

Rather than lecturing over nucleophilic substitution, the instructors supplied students with two activities (Straumanis, pp. 97-106; pp. 107-116). The first activity focused on one-step nucleophilic substitution (S_N2) while the second focused on two-step nucleophilic substitution (S_N1).

Both activities first supply a model for students to use as a reference. The model for the first activity is shown in Figure 2. Following this model are a series of critical thinking questions that start by building on previously covered concepts with an increasing level of difficulty for each subsequent question. For the first question, students were asked to identify both the incoming group and the leaving group for each reaction. This is followed by a question asking students to place δ+ and δ– above portions of each of the carbon reactants. For the final question, students need to use curved arrows to draw a reaction mechanism. An extended model follows, exploring such concepts as inversion of stereochemistry and reaction rates. In this manner, students can start out with a basic model that extends concepts covered previously (electronegativity and bond polarity) and applies them to new concepts (S_N2 reactions, leaving group ability, and reaction rates).

The second activity contained two models concerning S_N1 reactions, followed by a series of questions. For the first model, students needed to label carbocations as primary, secondary, or tertiary. When provided with energy diagrams students could compare the differences between these three to determine a stability trend. The second model focused on the rate-determining step, comparing the S_N1 reaction to the S_N2 reaction in activity 1 to uncover the differences between the two. The two activities conclude with a summary table (Table 3) that students fill in with the following points:

- Very polar solvent better, but weakly polar OK
- Very polar protic solvent required to stabilize ion intermediates
- Must be 2°, 3°, allyl or benzyl
- Methyl or 1° preferred, 2° OK too

Table 3 Summary of factors leading to S_N2 vs. S_N1 reactions

Reaction type	Solvent	Stereochemistry	Electrophile	Rate
S_N2				
S_N1				

- Dependent on the identity and concentration of both nucleophile and electrophile
- Dependent only on the identity and concentration of electrophile
- Inverted (switch from *R* to *S* or vice versa)
- Racemic mixture produced

These two activities required two lecture periods to complete followed by a third period used for finalization, double-checking, and review.

For the laboratory, a clear distinction between the traditional experiment and the guided-inquiry SWH experiment needs to be made. The title of the traditional experiment, *The preparation of 2-chloro-2-methyl propane*, was renamed as *Substitution vs. elimination: the chemical competition* (Schroeder *et al.*, pp. 43-48). This removed the expected answer from the title and allowed students to question what would happen during the experiment. The procedure was the same as that followed for the traditional experiment, but without the explicit details (*i.e.* which layer to remove during the extraction, what to look for in the infrared spectrum). One of the more distinctive aspects is how the new experiment builds upon knowledge gained from prior experiments. Earlier in the term, students performed a dehydration reaction, treating an alcohol with a strong acid to produce an alkene. In this new substitution experiment an alcohol is again reacted with a strong acid, but students find out that the amount of acid has changed. This leads students to wonder whether they will form what they did before or if something new will happen.

Results and discussion

Part 1: Exam performance

Our first objective was to compare the exam performance of the summer term students to that of the students who took the traditional course the semester before. To compare the two groups, we wrote two questions on the exam similar to questions on the prior exam (Figure 3). The first question was identical to the question given during the traditional course; students needed to draw the correct structure of the product. During the summer, 22 out of 23 students answered correctly. This is comparable to the performance of the students in the traditional course.

The second problem was a multi-step question combining three different types of questions. Performance on this question was mixed; 11 out of 23 students drew the major and the minor elimination products correctly. More importantly, 8 out of the 23 sketched a complete mechanism that showed the formation of both products. Nine of the students correctly explained why the more substituted alkene was produced.

Draw the structure of the product formed in the following reaction:

$CH_3CH_2C(CH_3)_2OH \xrightarrow{HCl}$

In the reaction below, the conditions favor an E1 reaction in which two possible products could form.
(a) 2 points – draw the structure of the two products;
(b) 4 points – Draw a reasonable reaction mechanism showing the formation of both products;
(c) 2 points – explain why the major product is formed.

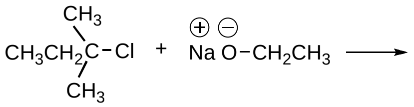


Fig. 3 Nucleophilic substitution and elimination exam questions.

It should be noted that during the previous semester, 111 students in the traditional course had had the opportunity to provide a mechanism for their reaction, but only twenty-eight actually tried and of these, only seven were correct. In terms of percentages, we were able to see an increase in the number of correct responses to the mechanism portion of this question (25% for the traditional group compared to 34% for the summer group). More importantly, every student who took the exam over the summer term attempted to solve the problem, whereas in the traditional course, 75% of the students did not attempt it. Partial credit was awarded for this mechanism with eleven out of the twenty-three students receiving 2 of the 4 points and three out of the twenty-three receiving 3 of the 4 points. Only one student during the summer term did not receive any points. What this shows is that while using the SWH format, students in the summer term were more confident in attempting the problem, and with one exception, the students were at least able to get it started.

In terms of performance on the corresponding nucleophilic substitution laboratory report during the summer term, the average score out of 24 points was 17.7, with only four students receiving a perfect score. Two of these students received full credit on both of the exam questions while the other two missed only one point on both of the questions. Thus, when compared to the students in the traditional setting, the students during the summer term received lower average scores on the corresponding laboratory report but performed much better on the corresponding exam. We continued using POGIL activities on other topics such as Grignard reactions, aldol reactions, and retrosynthetic analyses. Unfortunately, these types of questions were not asked of previous students in the traditional course so no comparison of problems can be made.

Part 2: Student perceptions

When we look at student perceptions of this course, it is clear that they shared many of the concerns that students before them did. When asked on the beginning survey what their expectations for this course were, nearly 40% of those who answered (8/19) believed that it was going to be more difficult than any other chemistry course they had taken. When asked whether their previous laboratory experience

Table 4 Student perceptions concerning laboratory work (beginning survey)

Question	Average
I would rather learn concepts in the lab before going to the lecture	2.9
The lab should help me understand concepts that are covered in the lecture	4.6
My past experience in the general chemistry lab should help me with this lab	3.8
I would rather learn concepts in the lab before going to the lecture	2.9
	Hours
On average, how much time do you expect to spend writing your laboratory report each time?	1.1 – 2.1

Table 5 End of term evaluation of the laboratory

Did the laboratory help you understand topics discussed in lecture?

Yes	16
Sometimes	3
No	0

Did the format of the lab report help you organize and put together your report?

Yes	18
No	1

How has this lab compared with the expectations you had for it at the beginning of the semester?

Easier	8
As expected	5
Harder	2
More interesting	2
More challenging	2
Other	2

On average, how much time did you spend writing each lab report?

1.3 – 1.9 hours

had been practical, almost half of those who answered said no (11/23). In addition, when asked what their primary reason for taking this course was all but three of them (21/24) said that it was a requirement. Not surprisingly, these results support the idea that organic chemistry is perceived as a difficult course. Other questions on the survey are shown in Table 4. These questions were based on a 1 – 5 Likert scale (1 – strongly disagree; 5 – strongly agree).

From the responses to the questions in Table 4, it would appear that students have a slight preference for addressing a concept in a lecture before going into the laboratory. The high level of agreement to the second question in which the laboratory should follow a lecture further corroborates this. Student comments indicated they wanted to *"learn in lecture before doing in the laboratory"*. Despite the number of negatives mentioned previously, students appeared to be much more confident when asked about their prior laboratory experience, and whether or not it would help them (surprising, in that many of the students thought their prior laboratory experiences in general chemistry were not practical). And when asked about the time commitment that would be required, they gave an average range between 1.1 – 2.1 hours to write a laboratory report.

At the conclusion of the summer class, students completed the end-of-term evaluation, with questions similar to those given on the beginning survey. These results are shown in Table 5. An overwhelming number of students believed the laboratory helped them understand topics discussed in lecture, even though many of the laboratory experiments addressed the topics prior to them being covered in the lecture. What this could mean is that exploring new concepts in the laboratory better prepares students for the activity-based lecture.

Concerning the SWH laboratory report format, all but one student thought it helped them organize their thoughts into a workable report. Four of these who agreed did express some reservation. Two of the students thought that some aspects of the report seemed repetitive, while another two were concerned that they never knew what the grader was looking for. The most compelling series of responses were to the question of how the laboratory was perceived at the end of the term compared to the expectations the students had for it at the beginning. At the end of the semester, eight students thought the laboratory was easier than what they had expected it to be. Still, five students said it had met their expectations, although none of these five wrote negative comments concerning the laboratory. Only two students thought the laboratory was as hard or harder than what they had expected going in. Finally, in terms of the time requirement, many students felt they spent nearly as much time writing each report as they expected to, although the higher end of the range is slightly lower than it had been in the beginning of the semester.

A separate evaluation was also given for the lecture. The major differences between our approach to this course compared to the previous traditional approach were the reliance on group work, activities, the laboratory—lecture correlation, and the removal of most of the lecturing.

According to Table 6, a majority of students found the activities helpful. Some of the students gave mixed responses, saying that some of the activities were very helpful whereas others were not. In terms of being in groups, again a majority of the students liked this approach better than the traditional lecture, although five students did see a need for a more balanced approach. When asked about the level of difficulty of the activities, students gave an overall average of 3.3 on a 5-point Likert scale (5 – much too difficult; 1 – much too easy). This seems surprising since many of the activities were geared toward undergraduate chemistry majors rather than non-majors.

In terms of the length of the activities, again students were in the middle, commenting that the length of each activity was about right. The last point to mention is the difference between the amount of time students expected to spend studying for class compared to the amount of time they actually spent studying for class. As can be seen from the table, this amount was less by roughly two hours. Taken together with the value given for the duration of the activities, these data suggest that most of the work done for this course took place during the class period.

Table 6 End of term evaluation of the lecture

Did you find the activities helpful in understanding the material?	
Yes	12
Sometimes	5
No	2
Did group work seem more beneficial for understanding concepts, or would more lecturing have been beneficial?	
Group work	9
Some combination	5
Lecture	5
In terms of the activity assignments, please rate the level of:	
Difficulty	3.3 (5 point scale)
Length	3.4
On average, how much time do you expect to spend studying for the lecture?	
5.5 – 9.1 hours	
On average, how much time did you spend studying for the lecture?	
3.6 – 7.1 hours	

Conclusions

The primary goal of implementing POGIL in the lectures along with the SWH format in the laboratory was to encourage students to think more critically while allowing them to construct their own knowledge. This is believed to have directly resulted in students achieving a higher success rate on what they initially perceived to be difficult questions (mechanisms). Students appeared more confident when attempting these types of questions than in the previous semester when a large majority of students skipped them. For the substitution example shown here, all but one student received at least half the points. Mechanisms are difficult for students to learn, even for chemistry majors. The fact that these students appeared to show this confidence was encouraging.

Another goal was to integrate the laboratory component of the course fully with the lecture component. We were deeply concerned that past students had received very high marks in the laboratory, but no correlation existed with the lecture marks. This was evident from student performance on laboratory reports during the traditional spring semester. For the nucleophilic substitution experiment, 32 students out of 111 received a perfect score on their laboratory report, which included a full mechanism showing the conversion of *tert*-butyl alcohol into *tert*-butyl chloride. Yet when asked to complete this same mechanism two weeks later on an exam, only five of these thirty-two students tried and only two of them were successful. During the summer, all students attempted this problem and the success rate increased.

We also wanted to see whether implementing these two methods would change student perceptions of the level of difficulty of organic chemistry. At the beginning of the summer term, the majority of the students reported that they were taking this class simply because it was required. Most were also expecting it to be a very hard class; some even remarked that it would be the hardest chemistry class they would ever have to take. But based on the end-of-term evaluations, it would appear that many of these students were surprised by what they initially thought. Despite these activities being geared toward chemistry majors, this group of students did not think the activities were too hard, and they did not think they were too long. Only two of the students did not think the activities to be helpful in guiding them to an understanding of the material. Their overall preference for group work, in addition to the decrease in the amount of studying outside of class, leads us to believe that most of the work was completed during the period.

Research has shown that each of these teaching methods on its own increases student performance and improves student attitudes. Combining these two together showed us that our students could be challenged with difficult questions and still perform well. Although this study only focused on one topic from one exam, the clear distinction between the performance of the two groups on this concept, and their perceptions of the course as a whole, is evident. To better compare the traditional approach to the guided inquiry approach it would be beneficial to implement these same strategies during a spring semester with the same instructor for both courses. During the spring, the time gap between the substitution laboratory experiment and the corresponding class exam was roughly two weeks. During the summer, this gap decreased to just a few days. It may be possible that information was stored in short-term memory, allowing students in the summer to be more apt to recollect it. Nevertheless, with the change in student perceptions regarding the level of difficulty, the amount of work, and the connection between the laboratory and the lecture, we feel confident that these results would be replicated in a future study.

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