JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

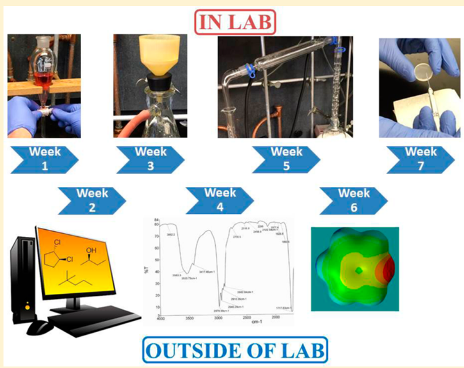
Comparable Educational Benefits in Half the Time: An Alternating Organic Chemistry Laboratory Sequence Targeting Prehealth Students

Sherri C. Young,* Keri L. Colabroy, and Marsha R. Baar

Department of Chemistry, Muhlenberg College, Allentown, Pennsylvania 18104, United States

Ⓢ *Supporting Information*

ABSTRACT: The laboratory is a mainstay in STEM education, promoting the development of critical thinking skills, dexterity, and scientific curiosity. The goals in the laboratory for nonchemistry, prehealth majors, though, could be distinguished from those for chemistry majors. In service courses such as organic chemistry, much laboratory time is often spent building discipline-specific technical skills that poorly align with the postgraduate goals of prehealth students. To address the needs of students in Muhlenberg College's organic chemistry course for nonchemistry majors, we developed a time- and resource-saving laboratory sequence that alternates traditional experiments with computer-graded self-guided inquiry activities. This innovative sequence requires approximately half the amount of reagents and fewer staff members, and it offers increased flexibility for students and instructors compared to a traditional (i.e., weekly) lab experience. When this model was offered in 2013–15, student performances on reports, notebooks, quizzes, exams, and the ACS Organic Chemistry Exam remained consistent with grades in prior course iterations even though students spent less time in lab. Student feedback on this model has been positive, and students felt they were better able to focus on individual lab assignments. We present a detailed overview of this model along with direct and indirect assessment data.



KEYWORDS: *Second-Year Undergraduate, Organic Chemistry, Laboratory Instruction, Inquiry-Based/Discovery Learning, Student-Centered Learning*

■ INTRODUCTION

Organic chemistry is a requirement for a large majority of undergraduate liberal arts biology, neuroscience, and prehealth majors, indicating that it is a valued fundamental in disciplines outside of chemistry. This course has also been a requirement for medical school admission since the mid 1970s, and the concepts of organic chemistry have been featured on the Medical College Admission Test (MCAT) since it was first introduced.[1,2] The MCAT 2015 revisions involved a shift away from traditional organic chemistry problems and toward chemistry presented in biological systems. In light of this change, many chemistry departments have revised their curricula to better fit the needs of prehealth students with biological interests.[3−5] The *Scientific Foundations for Future Physicians* (SFFP), a report addressing global concerns about education in premedical and medical school programs, suggests that chemistry departments should take into account the interests of the majority of their students when designing and teaching courses such as general and organic chemistry.[4]

Innovative curricular models geared toward premed students have been explored in recent years, perhaps stimulated by the SFFP. These models include the following: (1) separate tracks for chemistry and nonchemistry majors; (2) a hybrid organic chemistry, inorganic chemistry, and biochemistry course;[4] (3) a second-semester bioorganic course in lieu of traditional second-semester organic;[4] (4) the "organic first" approach;[6−8] and (5) the 1:2:1 approach (one semester of general chemistry, two semesters of organic, and one semester of general chemistry or biochemistry).[4] Certain curricular revisions have specifically involved the chemistry laboratory, and clearly, the requirement of a laboratory experience for prehealth students is less conserved across institutions. At some institutions, nonchemistry majors either enroll in one semester of lab (which may or may not be linked to the lecture)[9] or they do not have a lab experience. A writing-focused lab model that alternates traditional experiments with dry laboratories has been recently implemented at Duke University.[10] General chemistry[11] and physical chemistry[12] models involving the alternation of dry and wet laboratories have also been reported. These lab sequences are an innovative way to use time and resources more effectively, although they were not specifically geared toward prehealth students.

Although a small percentage of students enrolled in sophomore organic chemistry will pursue careers in chemistry,

Received: April 5, 2016
Revised: September 26, 2016

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 1. Comparison Between the Traditional Lab Sequence (2012−13) and the Alternating Lab Sequence (2013−14/2014−15) Schedules

Week	2012-13	2013-14/2014-15[a]
	Fall Semester	
1	Safety, check in, and notebooks; unknown white solid, part 1	Safety, check in, notebooks, and reports (for all students)
2	Reports; unknown white solid, part 2[25]	Carvone isolation, part 1
3	Extraction of caffeine from tea, part 1	Nomenclature of alkanes[26]
4	Extraction of caffeine from tea, part 2[27]	Carvone isolation, part 2[28]
5	No lab due to holiday	Nomenclature of functional groups[26]
6	Carvone isolation, part 1	Whiskey distillation[29]
7	Carvone isolation, part 2[28]	IR spectroscopy unknowns
8	S_N1 and S_N2 reactivities[27]	2-Methylcyclohexanol dehydration, part 1
9	Williamson ether synthesis, part 1	S_N1/S_N2 data interpretation[28]
10	Williamson ether synthesis, part 2[30,31]	2-Methylcyclohexanol dehydration, part 2[32]
11	Stilbene bromination[33]	E2 (F2013);[34] UV-vis (F2014)[35]
12	Microwave-accelerated alkyne hydration	Microwave-accelerated Diels-Alder[31]
13	Microwave-accelerated Diels-Alder[31]	Synthesis drill[36]
	Spring Semester	
1	TLC of analgesics[28]	TLC of analgesics[28]
2	^1H NMR spectroscopy unknowns	---
3	^{13}C NMR spectroscopy unknowns	Electrophilic aromatic substitution
4	Electrophilic aromatic substitution	NMR spectroscopy unknowns
5	Grignard, part 1	Grignard, part 1
6	Grignard, part 2	Mass spectrometry unknowns
7	Grignard, part 3 (analysis)[37]	Grignard, part 2[37]
8	No lab due to spring break	No lab due to spring break
9	Ester unknowns[31]	Spartan aromaticity[28]
10	Double aldol condensation[28]	Double aldol condensation[28]
11	No lab due to holiday	Nomenclature of amides, esters, amides[26]
12	Microwave-accelerated Suzuki coupling	Amide synthesis (S2014); reaction of dimedone with benzaldehyde (S2015)[38]
13	Amide synthesis, part 1	Amino acids, peptides, and proteins[39]
14	Amide synthesis, part 2	Lab practical and check out
15	Amide synthesis, part 3 (analysis)	Carbohydrates and lipids[39]

[a]Off-week activities are highlighted in gray. Brackets indicate where activities could be switched.

in our experience much of the laboratory time has been spent teaching discipline-specific technical skills, which are arguably less important to the nonmajor than process skills that transcend chemistry. The educational community is therefore calling on chemistry educators to better articulate the learning goals of the chemistry laboratory.[13,14] Clearly, some of the learning goals for a chemistry course require a laboratory experience. In the words of Reid and Shaw, "The absence of the laboratory experience may leave students with perceptions of chemistry that are very abstract and theoretical".[13] The lab can foster excitement about science and build creativity,[15] honesty, perseverance, and curiosity.[16] Some learning goals, however, can be accomplished outside of the laboratory (e.g., data interpretation). For nonchemistry majors, the goals accomplished *outside* of the laboratory may be as, if not more, important than those accomplished in the lab. For example, many organic chemistry experiments involve validation of the identity of a synthesized molecule.[17,18] While there are merits to this type of experiment, most notably the development of good laboratory technique under controlled conditions, one may question the rationale for incorporating several of these experiments into a given lab sequence. Since a critical part of these experiments is the data analysis, which students can readily do outside of lab, alternating dry laboratories with wet laboratories has added benefits, including reduced cost, waste generated, and time spent in the laboratory.

Self-guided inquiry pedagogies, such as process oriented, guided inquiry learning (POGIL)[19−22] and the science writing heuristic (SWH),[23] have become commonplaces in the classroom and the laboratory. Evidence shows that allowing students to make their own connections and take ownership of their learning improves learning and retention.[24] At Winona State University, the number of organic chemistry students who performed below the 25th percentile on the ACS Organic

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

Chemistry Exam decreased significantly when taught using POGIL versus a traditional lecture.[21] Furthermore, students enrolled in a SWH model, a student-centered, writing-focused approach in which students decide what questions to investigate and experiments to run, scored higher on critical thinking exercises than those enrolled in a traditional laboratory.[23] Finally, many of these pedagogic models promote the development of soft skills, such as time management, communication, and listening skills, which are valued in the workplace.

At Muhlenberg College, the organic chemistry laboratory curriculum was revised to dedicate more student time to process skills, which transcend chemistry and are useful in any discipline. By spending more time on critical reasoning, we strive to better fit the individual educational needs of all students enrolled in sophomore organic chemistry. This shift in emphasis was accomplished by alternating the weekly lab periods between hands-on laboratory exercises and self-guided inquiry activities that were performed outside of lab. Both direct and indirect assessments were used to measure the success of this model.

■ OVERVIEW OF MODEL

Schedule

The laboratory schedules for Muhlenberg's traditional (i.e., weekly; 2012−13) and alternating (2013−14/2014−15) laboratory sequences are presented in Table 1. Student enrollments all three years were typical of our department (70−80 students in the fall and 50−65 students in the spring). It should be noted that chemistry and biochemistry majors are advised to take a separate majors organic course; therefore, the students enrolled in this course were predominantly biology, neuroscience, and natural science majors, and a majority of these students were also prehealth. The laboratory periods in our department are 3 h long, and only 16 students can be in the laboratory at a given time. In the alternating sequence, a maximum of 32 students was enrolled in one time slot. Each lab was then split up into two 16-student sections (A and B). Following safety and check in at the beginning of the fall semester, section A performed laboratory experiments in the usual fashion while section B completed self-guided inquiry activities, which we will refer to as dry laboratories, alternate-week activities, or off-week activities, wrote laboratory reports, and watched technique videos. Then, the sections reversed their activities. This alternation was repeated, with a switch in the lead-off lab about midway through the semester (see the syllabi in the Supporting Information for more detailed lab schedules).

In this new model, students spent between 6 and 7 weeks per semester in the laboratory. Almost all of the experiments (~7 out of 9 per year) were modified to fit an inquiry-based model. Experiments were also carefully chosen such that students were exposed to critical laboratory techniques (e.g., extraction) at least twice throughout the year (see the Technique Competency section for more information). To support this approach, experiments such as carvone isolation[28] and the Grignard reaction[37] were preferable because they introduced students to multiple techniques and concepts in a short period of time. Moreover, microwave heating has shortened many of our synthetic organic experiments by dramatically reducing reaction times,[31,40] often allowing for synthesis, purification, and characterization to be accomplished in one lab period. Certain experiments from the nonalternating 2012−13 sequence were either eliminated if they did not accomplish the desired learning goals or converted into alternate-week exercises. For example, an experiment in which students measured rates for a series of S_N1 and S_N2 reactions[27] was replaced by a dry laboratory (Table 1). In the traditional sequence, weeks were dedicated solely to spectral analysis; in the revised sequence, these analyses were performed as dry laboratories. Together, these changes increased the efficiency of our lab curriculum while still introducing students to key lab techniques and developing their analytical and writing skills.

Self-Guided Inquiry Activities

Students completed 6 self-guided inquiry activities per semester focused on a range of topics (Table 1). These exercises were used to reinforce lecture material (e.g., spectroscopy, chemical mechanisms), build data interpretation and critical thinking skills, or, in some cases, introduce new material (e.g., proteins, nomenclature). Online homework/quiz platforms were used to administer and grade some of the alternate-week activities. These assignments comprised 20% of the laboratory grade, and average grades were in the mid-80s to low-90s each semester.

Some of the content-based activities focused on nomenclature. Since nomenclature is a systematic process whereby students execute a series of steps, it seems inappropriate to spend lecture time on this topic. Using Moreira's nomenclature handout as a model,[26] three nomenclature worksheets were prepared, with graduated difficulties. Prior to implementation of this new lab model, up to 20 min of lecture time per functional group had been spent on nomenclature. Incorporating nomenclature into the lab model freed up lecture time to insert biologically relevant content that tends to be omitted from a sophomore organic class due to time constraints. In addition, the biological content is better suited to the interests of nonchemistry majors and the career goals of prehealth students.

Report Writing

Report scaffolding,[41] by which students are introduced to one report section at a time, complemented this lab model nicely. Handouts focused on the abstract, results, or discussion sections of a formal report were provided for each experiment. Within each handout, students critiqued a mock report section and selected which types of information were suitable for each section. Scaffolding allowed lab instructors to provide students with more specific feedback on individual reports.

Technique Competency

In the alternating sequence, students were introduced to melting point analysis, liquid−liquid extraction, distillation (simple, steam, and fractional), rotary evaporation, IR and NMR spectroscopies, gas chromatography−mass spectrometry (GC−MS), refractometry, polarimetry, and vacuum filtration between 2 and 4 times throughout the year. In order to compensate for the decreased number of laboratory hours, a series of technique videos was prepared by our faculty using our instrumentation and made available to students through Vimeo.[42] Students were instructed to view the videos before lab and quizzed on video content to motivate compliance. By increasing student confidence and decreasing the amount of time spent on instructor demonstrations during the lab, these videos allowed the students to accomplish more in a 3 h period.

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 2. Comparison of Laboratory, Lecture, and ACS Organic Chemistry Exam Grades by Lab Approach

	Traditional Lab Sequence Grades, %[a]		Alternating Lab Sequence Grades, %[a]			
Graded Course Component	F2012, $N = 70$	S2013, $N = 56$	F2013, $N = 79$	S2014, $N = 66$	F2014, $N = 67$	S2015, $N = 48$
Lab reports	82.8 ± 13.6	83.2 ± 9.8	84.0 ± 7.0	87.5 ± 9.3	81.4 ± 9.1	90.0 ± 3.3
Prelab quizzes	80.0 ± 8.3	81.1 ± 8.1	74.9 ± 9.9	86.1 ± 12.3	88.8 ± 11.4	84.5 ± 6.4
Notebooks	81.1 ± 13.9	71.2 ± 18.9	68.9 ± 16.8	73.5 ± 17.2	79.2 ± 16.3	78.2 ± 2.5
Lab practical[b]	N/A	92.9 ± 5.6[c]	N/A	93.1 ± 5.1	N/A	84.8 ± 11.2
Lecture exams[d]	81.4 ± 8.0	79.7 ± 9.7	81.5 ± 8.9	84.7 ± 8.2	79.9 ± 9.5	85.6 ± 9.8
Final exam[e]	77.1 ± 9.6	N/A	83.2 ± 12.7	N/A	84.6 ± 12.4	N/A
ACS OChem exam[f]	N/A	60.4 ± 10.9	N/A	62.2 ± 10.7	N/A	62.3 ± 11.1

[a]Values are average student grades (%) ± standard deviations. [b]Laboratory practicals were administered at the end of the spring semesters only. [c]This average is from Muhlenberg's chemistry and biochemistry majors' organic chemistry course ($N = 21$). A lab practical was not administered in the nonchemistry majors' course in S2013. [d]Grade averages for three, 90 min lecture exams. [e]Grade averages for fall-semester 3 h final exams. [f]ACS Organic Chemistry Exams were administered as the final exam during the spring semesters only. The 2012 ACS exam was administered each year.

■ DIRECT ASSESSMENT

In general, student performance, measured by laboratory report grades, prelab quiz grades, lab notebook grades, 90 min lecture exam grades, fall-semester final exam grades, and ACS Organic Chemistry Exam grades (administered each spring), was consistent between our nonalternating (2012−13) and alternating lab sequences (2013−14/2014−15), as shown in Table 2. As we continue to optimize this model, we hope that student learning and performance will be improved in all areas of this course.

Laboratory Reports

When grading laboratory reports, similar rubrics and point allocations were used to minimize instructor-to-instructor and year-to-year grade variations. It is important to note that the same grading rubrics were not used each year since past organic chemistry students could theoretically have shared them with current students. Even with fewer writing exercises in this model, students performed as well as the students in the traditional model on lab reports (Table 2), likely in part because of the section-specific handouts provided in 2013−14 and 2014−15.

Prelab Quizzes

In the traditional and alternating lab models, weekly prelab quizzes, which quizzed students on safety, procedure, technique, theory, and physical properties of relevant compounds, were administered. Although different prelab quizzes were administered each year, to prevent past students from sharing their quizzes with current students, the compositions of the quizzes remained consistent, and similar types of questions were asked from year to year. There were larger variations in prelab quiz performances from semester to semester, especially between F2012 and F2013 (Table 2); however, the large standard deviations and grade variance among multiple instructors could explain this variation. Furthermore, prelab quiz grades were much more consistent across the spring semesters. In future years, we will continue to monitor student performance on prelab quizzes to ensure that this change has not had an adverse impact on student understanding of lab technique, theory, etc.

Notebook Grades

We observed a decrease in notebook grades between F2012 (traditional lab) and F2013 (alternating lab), although the F2014 notebook grades go back up to ∼80% (Table 2). Since the notebook grades between S2013, S2014, and S2015 are more consistent and trending upward, the F2013 notebook grades may have either been an anomaly or a result of large standard deviations and instructor-to-instructor variations. We will continue to monitor student notebook grades to ensure this new model has not negatively impacted student notebook keeping.

Lab Practicals

At the end of the S2014 and S2015 semesters, lab practicals were administered to assess technique proficiencies. Students were responsible for six techniques, melting point analysis, rotary evaporation, refractometry, vacuum filtration, simple distillation, and liquid−liquid extraction, and they were told in advanced that they would be randomly assigned two of these techniques. For each technique, stations containing the necessary equipment and glassware as well as "decoy" items (i.e., items not needed to perform the technique at hand) were set up. Throughout the practical, the instructor asked students questions about theory, which was part of the evaluation.

The lab practical averages from S2014 and S2015 are reported in Table 2. Although we did not administer a lab practical in S2013 (prechange) for direct comparison, the average lab practical grade for Muhlenberg's majors' organic chemistry course that year was 92.9 ± 5.6% ($N = 21$). This average serves as a benchmark of technique proficiency for students who attend organic chemistry lab every week. In general, a wider range of grades is observed in the nonchemistry majors' course compared to the majors' course, due to differences in class size and student interest in the material, which may explain the difference between the S2013 and S2015 lab practical grades. We contend that the technique videos, which were not available for students in 2012−13, played a key role in student development of technique proficiencies, despite fewer hours spent in lab. Additional details about the lab practicals, including grading criteria, can be found in the Supporting Information.

Exam Grades

Lecture exam, final exam, and ACS Organic Chemistry Exam grades were included in our overall assessment of this new lab model because, although these grades are not directly associated with the laboratory, one commonly cited learning goal for the laboratory is that it reinforces lecture content.[43] With that logic, students who spend less time in lab could perform less well on exams. This was not our experience, however, since student performances on 90 min lecture exams, fall-semester final exams, and the ACS Organic Chemistry Exam (administered each spring) were very consistent pre- and postchange (Table 2). To analyze these data in more detail, we

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

selected ACS Organic Chemistry Exam and fall-semester final exam questions focused on specific topics and compared student performances on those questions year to year (Table 3). Spectroscopy (IR and NMR), S_N1/S_N2, and nomenclature were chosen as topics because there was a suitable number of each type of question for analysis and, in each case, these topics were covered *in* the laboratory (or, in the case of nomenclature, in lecture) in the traditional sequence but *outside* of the laboratory in the alternating sequence (Table 1). For example, in F2012, students measured S_N1/S_N2 reaction rates in the laboratory whereas students interpreted S_N1/S_N2 rate data as an alternate-week activity in F2013/F2014. Students performed similarly on these content-specific questions from year to year, within standard deviation (Table 3). This consistency pre- and postchange suggests that some of the learning goals commonly associated with the laboratory (e.g., reinforcement of lecture content) could be achieved outside of the laboratory.

Table 3. Student Performance on Specific Types of Exam Questions Pre- and Postchange

	Av. Grades, %, by Laboratory Sequence		
	Traditional	Alternating	
Topic for Analysis	S2013, N = 56	S2014, N = 66	S2015, N = 48
Spectroscopy[a]	77.2 ± 15.5	79.6 ± 14.0	73.4 ± 16.9
S_N1 and S_N2[a]	63.4 ± 9.4	59.6 ± 8.2	69.8 ± 6.0
Nomenclature[b]	86.1 ± 9.1	81.7 ± 9.8	88.1 ± 11.0

[a]ACS Organic Chemistry Exam questions related to spectroscopy and S_N1/S_N2. [b]Fall-semester final exam nomenclature questions.

■ INDIRECT ASSESSMENT

In 2013−14, students were asked to complete detailed assessments of this new laboratory model. Selected assessment data are presented in Figure 1. Additional assessments posed at the end of each lab assignment encouraged metacognition by allowing students to reflect on their own learning.[44,45] When asked whether they would prefer an alternating or traditional sequence, 94% and 96% of students preferred the alternating sequence in S2014 and F2014, respectively. A formidable challenge will be discerning whether or not students felt they benefited educationally from the model or whether they just preferred to spend fewer hours in lab.

When asked about report writing on a Likert scale (1, strongly disagree; 5, strongly agree), students rated their understanding of the critical aspects of an abstract, results, and discussion section as a 4 out of 5. Student feedback on the technique videos has also been very positive. Several students expressed that they felt more confident and less stressed during the laboratory period, and that they wished they had technique videos for their other science courses. One student wrote, “I learned and remembered the lab techniques much better than in general chemistry because I would watch the technique videos and then reinforce knowledge by actually performing the techniques.” Anecdotally, lab instructors noticed that their lab students were less anxious, more efficient, and more confident in lab; many students specifically attributed these improvements to the videos.[42] When asked to rate the helpfulness of the videos, the clarity of background information, and their comfort performing each technique after viewing the videos, students responded 4.0, 4.0−4.4, and 4.0−4.7 out of 5, respectively. In F2014, when asked whether the videos helped them become proficient in critical organic chemistry lab techniques, the average response was 4.3 out of 5. Interestingly, ∼85% of students did not do additional background reading in a laboratory technique book, even though one was required in 2013−14. In the future, additional theory will be incorporated into each technique video; it is possible that a technique book is no longer necessary.

According to indirect assessment results, the majority of students used lecture notes, textbooks, and/or instructor guidance to complete the alternate-week activities, which took them 1−3 h on average to complete. Students were encouraged by the course professor to work in small groups on these

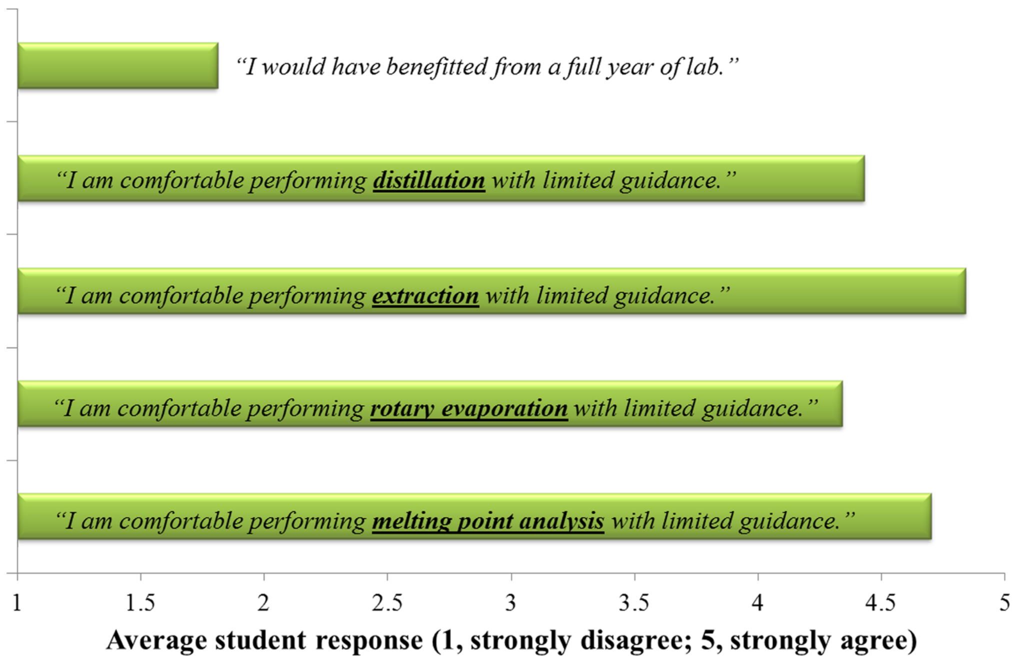


Figure 1. Selected assessment data from the spring of 2014.

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

assignments. Many students chose to work alone on the easier activities but in small groups on the more challenging ones.

We successfully utilized the alternate-week activities to introduce new material, such as nomenclature and biomolecules. In S2015, when students were asked to rate their comfort level naming specific functional groups and molecules with multiple functional groups, the average responses were between 3.0 and 4.2 out of 5, depending on the functional group. (Generally, students rated their comfort naming carboxylic acids, esters, and amides the lowest.) These data are corroborated by the direct assessment data on nomenclature presented in Table 3 (vide supra). Students also rated their understanding of amino acids and related concepts between 3.6 and 4.2 out of 5.

At the end of the assessment forms, students were asked to provide additional comments on the new model. One student mentioned that, since there were fewer lab reports required throughout the year, she put much more effort into individual reports. Another stated, "I really liked having the alternating lab model because it allowed me to fully prepare and focus on what I was learning". A few students did have concerns about this model. One student questioned whether or not reducing the number of lab hours would effectively prepare premedical students for the MCATs. This is a question that our department will continually assess.

■ ADVANTAGES OF THE MODEL

Science, technology, engineering, and math (STEM) education research suggests that students learn best when they are actively engaged with the material at hand.[44] This new lab model, in which almost all of the work is inquiry-based, allows students to take ownership of their learning by constructing their own explanations for key chemistry phenomena, which enhances learning.[44,45] Also, many of these self-guided inquiry activities require students to use previous knowledge in a new context, a skill necessary in any discipline. Furthermore, many students work in groups on the alternate-week exercises; evidence suggests that collaboration can improve learning and retention.[44,45]

Pedagogically, we shifted the focus of the organic chemistry laboratory toward nontechnical skills, which are useful in any discipline. The nonchemistry majors enrolled in this course will not have to physically perform lab techniques as part of their careers; however, these students will be expected to analyze and interpret data and come to a reasonable conclusion based on those data. In this way, the alternating lab model may more effectively prepare nonchemistry majors for their careers.

At institutions that offer a separate general chemistry course for chemistry majors, this model could be readily implemented into general chemistry. Chemistry departments could feasibly coordinate with biology, math, or physics departments so that students could alternate chemistry lab with another lab. Two laboratories would then only require one 3−4 h time slot per week, giving students increased flexibility to schedule internships, volunteer work, shadowing, or research experiences. This model also provides the course professor with flexibility; she could choose self-guided inquiry activities based upon the needs of her students. Moreover, the alternate-week activities could serve as an opportunity to integrate additional literature searching and reading into the chemistry curriculum.

Other secondary benefits of this model include the reduced cost of staffing, laboratory supplies, and waste disposal. Before this change was implemented, our department hired adjunct faculty to fill in organic chemistry laboratories, often with high turnover. With this new model, we can usually cover all lab sections internally, which cuts down on the amount of faculty time spent training adjuncts. Finally, when compared to models that offer one semester of lab (which could be taken at any time), this alternating sequence allows students to more readily make connections between the lecture and the laboratory.

■ REMAINING CONCERNS

There are some issues with this model that will need to be addressed in the future. Chemistry departments offering one organic course for chemistry and nonchemistry majors may consider implementing a revised version of this model, since chemistry majors who enroll in an alternating sequence could be less proficient at performing techniques in upper level courses or during research. A potential solution would be to group all students together in lecture and then offer a separate, nonalternating laboratory experience for chemistry majors. The advising of students who enroll in the alternating sequence and declare a chemistry or biochemistry major later on may also be a challenge. Since ACS requires 400 lab hours,[46] said students would need additional lab hours to receive certification. This could readily be accomplished with a research experience in combination with a lab-containing advanced course. Finally, it is possible that reducing the number of lab hours could have an adverse effect on student development of dexterity, although this was not our experience.

Reduced cleanliness during lab was an unforeseen consequence of this model. Since students only attended lab every other week, they were messy during lab, even after multiple warnings from the instructor. Anecdotally, students seemed to forget the waste disposal protocols more frequently than students in a traditional lab. This may not have been a result of carelessness; students simply were not spending enough time in lab to get sufficient reinforcement of these rules.

After presenting this model to several faculty members at Muhlenberg and elsewhere, we have received mixed reactions. One argument that has been made against this model is that reactions covered in lecture are reinforced when students perform said reactions in the laboratory. As such, students who spend less time in lab could have a lower understanding of the course material. This was not our experience as student performances in various aspects of the course were comparable pre- and postchange (Tables 2 and 3). Chemistry departments interested in implementing this model, however, should use both direct and indirect assessments to ensure student learning is not adversely impacted by this change.

■ CONCLUSION

An organic chemistry lab model for nonchemistry majors has been offered at Muhlenberg College since F2013. In this model, students alternate inquiry-based experiments with self-guided inquiry activities performed outside of lab. Students gain exposure to critical laboratory techniques and develop analytical, problem solving, and soft skills, which transcend chemistry. This model provides students and instructors with increased flexibility, and it saves time and resources compared to a traditional lab that meets every week. Detailed direct and indirect assessments suggest students sufficiently developed technique proficiencies and report writing skills, despite fewer hours spent in lab. Overall, student feedback has been positive, and student performance in all components of the course has

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

remained consistent pre- and postchange. The success of this model is likely, in part, due to the technique videos and alternate-week activities, which are a significant time investment initially but worth it in the long term. Our department will continue to optimize this model in the hopes of improving learning outcomes for prehealth students.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00254.

Laboratory syllabi for 2012−13 and 2014−15, implementation and grading notes, lab practical details, and indirect assessment questions (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: young@muhlenberg.edu.

Notes

The authors declare no competing financial interest.
Technique videos used in 2013−14 and 2014−15 can be found at https://vimeo.com/channels/organicchemistry.

■ ACKNOWLEDGMENTS

The authors thank past Muhlenberg students Zachary Shuler ('15) and Rachel Halpern ('14) for organizing the indirect assessment data and providing valuable feedback on this lab model. We thank Muhlenberg's Faculty Center for Teaching, the chemistry department, the Office of the Provost, and the Office of Information Technology for providing funding and support for this program. We are grateful to the organic chemistry students from 2013−15 for filling out multiple assessment forms and providing honest feedback about this model.

■ REFERENCES

(1) McGaghie, W. C. Assessing Readiness for Medical Education: Evolution of the Medical College Admission Test. *JAMA* **2002**, *288* (9), 1085−1090.
(2) Muller, D. Reforming Premedical Education–out with the Old, in with the New. *N. Engl. J. Med.* **2013**, *368* (17), 1567−1569.
(3) Brenner, C. Rethinking Premedical and Health Professional Curricula in Light of MCAT 2015. *J. Chem. Educ.* **2013**, *90* (7), 807−812.
(4) Shulman, J. I. Chemistry in the Premedical Curriculum: Considering the Options. *J. Chem. Educ.* **2013**, *90* (7), 813−815.
(5) Carroll, M. K. Moving from Recommendations to Innovations: Increasing the Relevancy and Effectiveness of Chemistry Education. *J. Chem. Educ.* **2013**, *90* (7), 816−819.
(6) Reingold, I. D. Bioorganic First: A New Model for the College Chemistry Curriculum. *J. Chem. Educ.* **2001**, *78* (7), 869−871.
(7) Ege, S. N.; Coppola, B. P.; Lawton, R. G. The University of Michigan Undergraduate Chemistry Curriculum 1. Philosophy, Curriculum, and the Nature of Change. *J. Chem. Educ.* **1997**, *74* (1), 74−83.
(8) Coppola, B. P.; Ege, S. N.; Lawton, R. G. The University of Michigan Undergraduate Chemistry Curriculum 2. Instructional Strategies and Assessment. *J. Chem. Educ.* **1997**, *74* (1), 84−94.
(9) Foster, K. A.; Moody, A. E. The Organic Lab: A Status Quo Report and a Two-Semesters-in-One Approach. *J. Chem. Educ.* **1997**, *74* (5), 587−591.
(10) Schmitt, A. A.; Parise, J. A. Introducing Scientific Writing in a Second Semester Organic Chemistry Laboratory Course. In *Advances in Teaching Organic Chemistry*; Duffy-Matzner, J. L., Pacheco, K. A. O., Eds.; American Chemical Society, Series Ed.; American Chemical Society: Washington, DC, 2012; Vol. *1108*, pp 51−71.
(11) Nussbaum, S.; Nakonechny, J.; Lomas, C. *Mixed-Mode Guided Inquiry Chemistry Laboratory: Changing the First-Year Experience*; Presented at the 225th ACS National Meeting, New Orleans, LA, 2003; CHED 1168.
(12) Karpen, M. E.; Henderleiter, J.; Schaertel, S. A. Integrating Computational Chemistry into the Physical Chemistry Laboratory Curriculum: A Wet Lab/Dry Lab Approach. *J. Chem. Educ.* **2004**, *81* (4), 475−477.
(13) Reid, N.; Shah, I. The Role of Laboratory Work in University Chemistry. *Chem. Educ. Res. Pract.* **2007**, *8* (2), 172−185.
(14) Bruck, A. D.; Towns, M. Development, Implementation, and Analysis of a National Survey of Faculty Goals for Undergraduate Chemistry Laboratory. *J. Chem. Educ.* **2013**, *90* (6), 685−693.
(15) *Second Handbook of Research on Teaching; A Project of the American Educational Research Association*; Gage, N. L., Travers, R. M. W., American Educational Research Association, Eds.; Rand McNally: Chicago, 1973.
(16) *The Structure of Science Education*; Gardner, P. L., Ed.; Longman Australia: Hawthorn, Vic, Australia, 1975.
(17) Pickering, M. A Physical Chemist Looks at Organic Chemistry Lab. *J. Chem. Educ.* **1988**, *65* (2), 143−144.
(18) Mohrig, J. R. The Problem with Organic Chemistry Labs. *J. Chem. Educ.* **2004**, *81* (8), 1083−1085.
(19) Hammond, C. N.; Mohrig, J. R.; Colby, D. A. On the Successful Use of Inquiry-Driven Experiments in the Organic Chemistry Laboratory. *J. Chem. Educ.* **2007**, *84* (6), 992−998.
(20) Schoffstall, A. M.; Gaddis, B. A. Incorporating Guided-Inquiry Learning into the Organic Chemistry Laboratory. *J. Chem. Educ.* **2007**, *84* (5), 848−851.
(21) Hein, S. M. Positive Impacts Using POGIL in Organic Chemistry. *J. Chem. Educ.* **2012**, *89* (7), 860−864.
(22) Moog, R. S.; Farrell, J. J. *Chemistry: A Guided Inquiry*, 6th ed.; John Wiley & Sons: New York, 2015.
(23) Gupta, T.; Burke, K. A.; Mehta, A.; Greenbowe, T. J. Impact of Guided-Inquiry-Based Instruction with a Writing and Reflection Emphasis on Chemistry Students' Critical Thinking Abilities. *J. Chem. Educ.* **2015**, *92* (1), 32−38.
(24) *Handbook of Research on Science Teaching and Learning*; Gabel, D., National Science Teachers Association, Eds.; Maxwell Macmillan International: Toronto, 1994.
(25) Coppola, B. P.; Lawton, R. G. "Who Has the Same Substance That I Have?": A Blueprint for Collaborative Learning Activities. *J. Chem. Educ.* **1995**, *72* (12), 1120−1122.
(26) Moreira, R. F. A Game for the Early and Rapid Assimilation of Organic Nomenclature. *J. Chem. Educ.* **2013**, *90* (8), 1035−1037.
(27) Schoffstall, A. M.; Gaddis, B. A.; Druelinger, M. L. *Microscale and Miniscale Organic Chemistry Laboratory Experiments*, 2nd ed.; McGraw-Hill Higher Education: New York, 2004.
(28) Mohrig, J. R. *Modern Projects and Experiments in Organic Chemistry: Miniscale and Williamson Microscale*, 2nd ed.; W.H. Freeman: New York, 2003.
(29) Wan, H.; Djokic, N.; Brown, B. A.; Kwon, Y. Using Whiskey-Flavoring Compounds To Teach Distillation and IR Spectroscopy to First-Semester Organic Chemistry Students. *J. Chem. Educ.* **2014**, *91* (1), 123−125.
(30) Baar, M. R.; Falcone, D.; Gordon, C. Microwave-Enhanced Organic Syntheses for the Undergraduate Laboratory: Diels−Alder Cycloaddition, Wittig Reaction, and Williamson Ether Synthesis. *J. Chem. Educ.* **2010**, *87* (1), 84−86.
(31) Baar, M. R.; Gammerdinger, W.; Leap, J.; Morales, E.; Shikora, J.; Weber, M. H. Pedagogical Comparison of Five Reactions Performed under Microwave Heating in Multi-Mode versus Mono-Mode Ovens: Diels−Alder Cycloaddition, Wittig Salt Formation, E2 Dehydrohalogenation To Form an Alkyne, Williamson Ether Synthesis, and Fischer Esterification. *J. Chem. Educ.* **2014**, *91* (10), 1720−1724.

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX

(32) *Organic Chemistry Laboratory: Standard and Microscale Experiments*, 2nd ed.; Bell, C. E., Rodig, O. R., Eds.; Saunders College Pub: Forth Worth, 1997.
(33) Williamson, K. L.; Masters, K. M. *Macroscale and Microscale Organic Experiments*, 6th ed.; Brooks/Cole: Belmont, CA, 2011.
(34) Leone, S. A.; Davis, J. D. The Dehydrohalogenation of 2-Bromobutane: A Simple Illustration of Anti-Saytzeff Elimination as a Laboratory Experiment for Organic Chemistry. *J. Chem. Educ.* **1992**, *69* (6), A175.
(35) Wade, L. G. *Organic Chemistry*, 8th ed.; Pearson: Boston, 2013.
(36) Straumanis, A. *Organic Chemistry: A Guided Inquiry: A Process Oriented Guided Inquiry Learning Course*; Houghton Mifflin: Boston, MA, 2009.
(37) Williamson, K. L. *Organic Experiments*, 9th ed.; Houghton Mifflin: Boston, 2004.
(38) Reeve, A. M. Reaction of Dimedone and Benzaldehyde: A Discovery-Based Lab for Second-Semester Organic Chemistry. *J. Chem. Educ.* **2015**, *92* (3), 582−585.
(39) Garoutte, M. P. *General, Organic, and Biological Chemistry: A Guided Inquiry*; John Wiley & Sons, Inc: Hoboken, NJ, 2007.
(40) Barnhardt, E. K.; Katritzky, A. R.; Cai, C.; Collins, M. D.; Scriven, E. F. V.; Singh, S. K. Incorporation of Microwave Synthesis into the Undergraduate Organic Laboratory. *J. Chem. Educ.* **2006**, *83* (4), 634−636.
(41) Deiner, L. J.; Newsome, D.; Samaroo, D. Directed Self-Inquiry: A Scaffold for Teaching Laboratory Report Writing. *J. Chem. Educ.* **2012**, *89* (12), 1511−1514.
(42) Colabroy, K. Organic Chemistry. https://vimeo.com/channels/organicchemistry (accessed Sep 2016).
(43) Boud, D.; Dunn, J.; Hegarty-Hazel, E. *Teaching in Laboratories*; Society for Research into Higher Education & NFER-Nelson: Guildford, Surrey, U.K., 1986.
(44) Kober, N. *Reaching Students: What Research Says about Effective Instruction in Undergraduate Science and Engineering*; The National Academies Press: Washington, DC, 2015.
(45) National Research Council (U.S.). *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*; Singer, S. R., Nielsen, N., Schweingruber, H. A., Eds.; The National Academies Press: Washington, DC, 2012.
(46) *Undergraduate Professional Education in Chemistry*; American Chemical Society: Washington, DC, 2008; p 5.

DOI: 10.1021/acs.jchemed.6b00254
J. Chem. Educ. XXXX, XXX, XXX−XXX