

Development and Implementation of a Two-Level Inquiry- and Project-Based Modular Approach to Teaching a Second-Semester Physical Chemistry Laboratory Course

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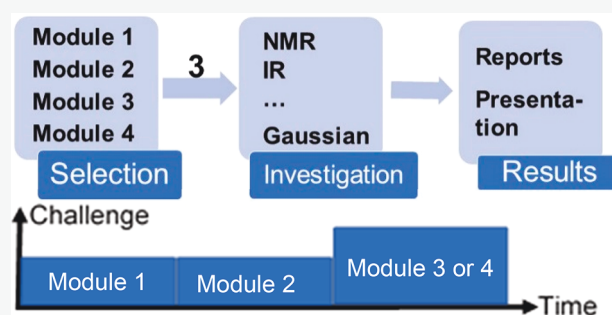
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ABSTRACT: Over the past 20 years, significant effort has been devoted to advancing the modular approach to teaching chemistry laboratory courses. The development and implementation of two modules are presented here for teaching a second-semester physical chemistry laboratory course using the modular approach: an inquiry-based module concerning proteins and a project-based module concerning organic small molecules. Each module focuses on a molecular system in question and allows participating students to choose and apply various methods to study the system in different ways, according to the advantages and disadvantages of each method. The common thrust of all of the modules is to develop students' critical thinking skills, provide them a conduit to apply their knowledge to real applications, encourage them to model the approaches and behavior of practicing scientists, and excite them to initiate and pursue research opportunities. Details of implementation of this modular approach in teaching the second-semester physical chemistry laboratory for the past 11 years are provided. The assessment results indicate encouraging evidence that this two-level modular approach has achieved its goals and assisted students in choosing more research-based careers.

KEYWORDS: Upper-Division Undergraduate, Physical Chemistry, Laboratory Instruction, Inquiry-Based/Discovery Learning



INTRODUCTION

Development of inquiry- or project-based modules to teach chemistry laboratory courses has made great progress since 1990.¹ Both inquiry- and project-based modules can be used to provide ample opportunities for students to practice and develop higher-order thinking skills, help students understand problems with a holistic view, and offer opportunities to design experiments. Qualitative assessment of inquiry-based teaching methods has been reported,² as have been descriptions of the differences in learning outcomes of project-based and inquiry-based learning activities.¹ A number of inquiry-based modules for advanced lab courses have been developed previously, such as one for NMR of a phospholipids;³ modules for materials science;⁴ a module for probing gold nanoparticle interfacial phenomena;⁵ modules used in organic chemistry classrooms;⁶ modules focusing on macromolecular chemistry in foundation courses;⁷ and pedagogical modules for increasing indigenous students' involvement in chemistry⁸—to mention only a few. Furthermore, there are modules using computational modeling to help teach upper-year materials chemistry.⁹ Indeed, such project-based efforts were already being implemented by the late nineties.¹⁰ A particular focus for project-based learning efforts has concerned laboratory courses¹¹ (including for online chemistry courses¹²), with the goal of improving student engagement and performance;¹³ related efforts have

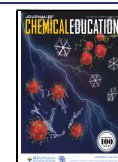
explored the role of scaffolds—methods of supervision—in project-based learning in undergraduate laboratories.¹⁴ Assessments of students' critical thinking skills in the context of using different approaches have also been reported (e.g., ref 15.).

Since 2011, we have developed and implemented a two-level modular approach in teaching the second-semester physical chemistry laboratory course. The primary goals with this course are to further develop students' critical thinking skills, provide students a platform to apply their knowledge to solve real problems, encourage them to model the approaches and behavior of practicing scientists, and excite them to initiate and pursue research opportunities. The motivation also comes from the desire to address what we perceive as one of the biggest problems in typical physical chemistry curricula, which is the competition between the amounts of material that must be covered with the depth at which such material should be covered. Too often, this problem is resolved in great favor of

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“breadth”, causing undergraduate physical chemistry to become an archetypal example of a scientific curriculum that is “a mile wide and an inch deep”.^{16,17} For example, it can be difficult, if not impossible, to cover all of the important topics in Atkins’ Physical Chemistry with anything close to the desired depth; this problem may result in “sampling”, which can lead overwhelmed students to resort to rote memorization of methods and equations—without attaining the (far more important) general understanding of key, underlying concepts. We use the modular approach in physical chemistry laboratory course as part of our larger strategy to deliberately sacrifice breadth for the sake of achieving greater depth in the material covered.

Therefore, the second semester physical chemistry lab course has been changed dramatically to introduce students to a host of modern methods, instrumentation, and systems of interest in physical chemistry using the modular approach. As a part of this effort, we have developed four modules and taught the second-semester physical chemistry laboratory course using variants of these modules for over 10 years. These four modules are classified into two levels, primarily according to the level of inquiry. The first level is composed of inquiry-based modules, whereas the second level is composed of project-based modules. The distinctions between the two levels also stem from the nature and outcome of each module. While both sets of modules technically belong to inquiry teaching, an inquiry-based module is centered on understanding notable phenomena of the molecular system of interest and on developing skills of utilizing different instrumentation/techniques with level 1 or level 2 of inquiry (i.e., guided inquiry or open inquiry), whereas each project-based module aims to investigate some fundamental aspects of a molecular system derived from a *current* “real-life” research project being conducted by faculty in the School with level 2 or level 3 (authentic inquiry) of inquiry. In inquiry-based modules, the student investigations and their results tend not to change or develop significantly from year to year. In contrast, the project-based modules are themselves part of a larger body of timely research and tend to evolve year after year to reflect the coherent development of the larger research project over time. For example, a given project-based module may be revised in a subsequent year by including the findings from previous years as background knowledge. Although student reports are generated from modules of both levels, the reports arising from the project-based modules are also more likely to become a part of a manuscript for journal publication. Furthermore, the inquiry- and project-based modules are offered sequentially over the course of the semester. Experiences gained from the inquiry-based modules at the beginning of the lab course serve as stepping stones for students to perform the more challenging project-based modules, thereby helping to ensure proper progress. The two inquiry-based modules are designed around specific questions (instead of stated goals or directives) that students are asked to consider and explore, whereas the two project-based modules are associated with standing, ongoing research projects in actual research laboratories in the School. However, modules of both levels still share the molecular systems-oriented, multimethod, multiweek modular structure. The list of modules developed and details of implementation and a typical course schedule are provided in [Tables S1 and S2](#) of the Supporting Information (SI), respectively. In what follows, we present two modules as examples: one inquiry-based module concerns the study of

structure, stability, and spectroscopic properties of proteins and their prosthetic groups and one project-based module that allows students to investigate the optical properties of organic small molecules and their applications as luminescence sensors. Following descriptions of these modules, the implementation including the choice of proper guidance¹⁸ in supervising the laboratory course with the new approach, the outcomes, and the assessment are then discussed.

■ INQUIRY-BASED MODULE: STRUCTURE, STABILITY, AND SPECTROSCOPY OF PROTEINS AND THEIR PROSTHETIC GROUPS

The goal of this module is to introduce students to one of the greatest “applications” of physical chemistry to biological systems—the study of protein folding and stability. This module serves as a physical chemistry student’s first introduction to this important and immensely rich subject matter. As such, the background material for the module places particular care with the exposition of key concepts, which include: amino acids and the peptide bond; the effects of hydrogen bonding; the hydrophobic effect; molecular (core) packing; the definitions and different types of primary, secondary, and tertiary structure; the relationship between structure and biological function; the “protein folding problem” (and its inverse); the role of dynamics; “molten globules”; and the (potentially devastating) pathological consequences of protein “misfolding”. While various proteins would be potentially suitable for the module, myoglobin is a natural choice because of its well-understood behavior and biological role and its likely familiarity (by name) with most students (not to mention its use in an excellent biophysical laboratory involving fluorescence studies of protein folding¹⁹). Protein samples will be exposed to heat, chemical denaturants, and/or pH changes to controllably unfold the protein; the folding/unfolding behavior will be subject to investigation using an array of different techniques and instrumentation, including differential scanning calorimetry, UV–vis spectroscopy, variable-temperature NMR, and fluorescence spectroscopy, among others. One approach students may choose is to prepare apomyoglobin by removing the prosthetic heme group using established (and facile) chemical means^{20,21} or even reconstitution of the protein with heme or other appropriate porphyrins, allowing for comparisons of the relative stabilities and spectroscopic properties of the different variants.

Several questions will arise from such investigations (see the [SI](#) for some examples); this module will train students to:

- Search the relevant literature
- Choose experimental approaches in consideration of available instrumentation (and their respective advantages and limitations)
- Prepare their experiments based on published protocols that students find during their literature search
- Communicate effectively within their group
- Document their results carefully
- Write their report through critical analysis of the data

The experimental and computational methods available to students for this module include: variable-temperature (VT) NMR spectroscopy, VT circular dichroism spectroscopy, infrared (IR) spectroscopy, UV–vis spectroscopy, fluorescence spectroscopy, differential scanning calorimetry, and polarizing optical microscopy, among others that have been available. Furthermore, students will also be able to use modern

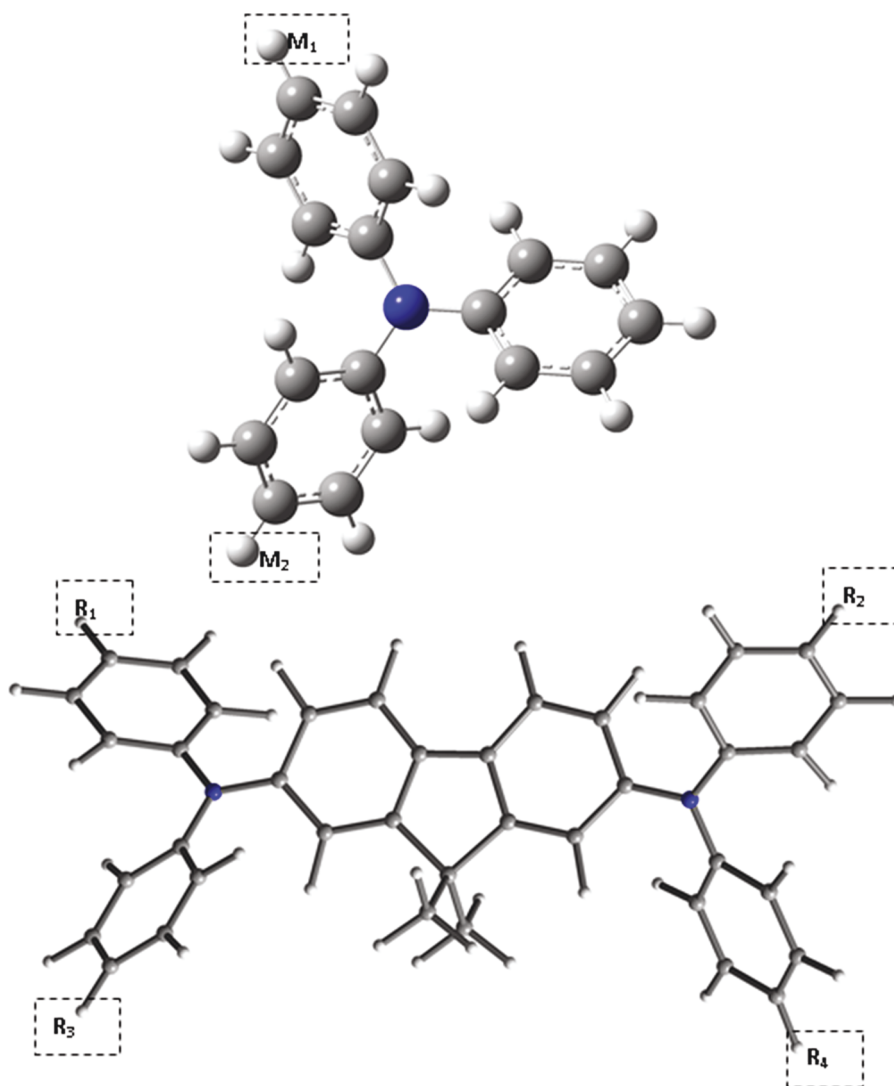


Figure 1. Structures of triphenyl amine (**1a**) and a derivative (**1b**) (top): **1a** ($M_1 = M_2 = H$) and **1b** ($M_1 = H$; $M_2 = CH_3$). Structures of 2,7-di(*N,N*-diphenylamino)-9,9-dimethyl-9*H*-fluorene (**2a**) and derivatives (**2b**, **2c**, **2d**, **2e**) (bottom): **2a** ($R_1 = R_2 = R_3 = R_4 = H$), **2b** ($R_1 = R_2 = OCH_3$, $R_3 = R_4 = H$), **2c** ($R_1 = R_2 = R_3 = R_4 = OCH_3$), **2d** ($R_1 = R_2 = NO_2$, $R_3 = R_4 = H$), and **2e** ($R_1 = R_2 = R_3 = R_4 = NO_2$). Atoms: N = blue, C = gray, and H = white.

quantum computational methods via Gaussian16 software to study structures and properties of molecules (e.g., the prosthetic heme group, with and without ligands, as well as other porphyrins) and will be able to utilize a variety of other software packages, including Origin and Mathematica for data analysis and making figures, MestreNOVA for processing and analyzing NMR data, and Chem3D, GaussView, etc., for drawing and visualizing molecular structures. All of these software packages are available in the computer lab for use. For this module, various web-based resources will be important (e.g., the Protein Data Bank or PDB).²²

Students are expected to complete five or six key activities in the span of 4 weeks depending on their own design of experiments: (1) develop a protocol for the preparation of apomyoglobin ("apo-Mb", i.e., Mb without the heme) from lyophilized horse skeletal muscle Mb and have it approved by the instructor/teaching assistants (TAs); (2) draw an accurate 3-D structure of the heme prosthetic group using GaussView and perform a structural optimization calculation using Gaussian software; (3) design an experiment (or experiments) to monitor Mb vs apoMb unfolding as a function of the

application of denaturing agents; (4) perform NMR experiments if students choose NMR as a tool and/or (5) perform UV-vis and/or fluorescence experiments to study met-Myoglobin unfolding; and (6) compare the spectra of different Mb variants, such as met-Mb, oxyMb, deoxyMb, met-Mb, etc., and compare with the calculated results based on the optimized structure of the prosthetic group.

While developing these activities, students will also be provided with several questions to answer that are shown in the SI. This module has been used since 2011 during the first 4-week period of the second-semester physical chemistry laboratory course. A general schedule is provided in Table S3 of the SI, which has some similarities to a flowchart on implementation by Quattrucci in using a problem-based approach to study the thermodynamics of DNA complex formation and photoreduction of benzophenone.²³ Starting from a literature search and background study, students then go on to discuss and design experiments before performing them. These procedures are transferable in the implementation of the modular approach, but the timeline is shorter: one

semester in the case of Quattrucci's work and 4 weeks in the current modular approach.

PROJECT-BASED MODULE: ELECTRONIC AND SPECTROSCOPIC PROPERTIES OF ORGANIC SMALL MOLECULES

Computational Chemistry has witnessed the most dramatic advances since the appearance of the Schrodinger equation and has played an increasing role in modern scientific research. More importantly, the advances in computational chemistry have made teaching quantum chemistry, a second-semester physical chemistry lecture course, more relevant and exciting. One of the authors (L.W.) teaches regularly the second-semester physical chemistry lecture course using the McQuarrie textbook²⁴ coupling with a POGIL teaching method.^{25,26} To demonstrate the power of quantum chemistry as a research tool and enhance students' understanding of the concepts in quantum chemistry and other related course materials, this project-based module was developed in 2020 and first implemented in spring 2022.

Project-based modules based on the current research of instructors have been developed in teaching laboratory courses ranging from developing inexpensive yet active catalysts for solar energy conversion,²⁷ monitoring water environment in lakes,²⁸ and understanding the properties of the molecules in refs 29 and 30. Using computation as the method of interest, project-based modules³¹ and virtual laboratories³² have previously been developed. In the present work, the main objectives of this computational module are to challenge students to explore the functions of various modern quantum chemistry software packages and to design calculations to study electronic and optical properties of small organic molecules. Students will be introduced to the important roles that various small organic molecules have played (and continue to play) in the efforts to solve grand challenges that the world faces, such as those concerning the environment,³³ water treatment,³⁴ and energy.³⁵ Furthermore, students will be required to design molecules using different functional groups³⁶ or new molecules³⁷ to generate Wannier excitons.³⁸ Examples of initial molecules presented to students are shown in Figure 1.

Students will be provided, as independent reading, with background material in the form of references for the module with exposition of key concepts, which include: excitons, bond conjugation and degeneracy; the effects of functional groups on electronic and optical properties; the relationship between structure and properties; fluorescence; phosphorescence; and the role that the relative positions of electronic energy levels play in determining fluorescence and phosphorescence properties. While various molecules would be potentially suitable for the module, triphenyl amine derivatives shown in Figure 1 are a natural choice for the project because of their promising characteristics underlying a class of recently discovered persistent luminescence materials.²⁹ Students will design their own calculations using Gaussian 16 to obtain properties of interest and generate IR spectra, UV–vis spectra, and fluorescence spectra, among others. Several initial questions provided to promote the students' efforts to develop their own questions through their investigations, as suggested in the SI.

Overall, this module aims to train students to:

- Search the relevant literature and update their knowledge through regular (weekly) reading of journal articles

- Design their calculations to study properties of interest
- Communicate effectively within their group
- Document their results carefully
- Write their report through critical analysis of the data and with the use of Endnote in citation of references

To make a smooth transition from scientific research to undergraduate classroom instruction, we first developed and implemented various project-based modules in graduate courses. The outcomes of these discovery-based learning opportunities included publications concerning a wide range of research topics from developing computer programs to the study of the effect of cooling rate on the formation of metal nanoparticles^{39,40} (such as Ag⁴¹ and Ir⁴²), to performing DFT calculations to study molecules as sensitizers,^{43,44} or to investigate the chemical properties of catalytic surfaces.⁴⁵ These practices and experiences in teaching graduate courses provided us with useful guidance and tools to implement the currently designed project-based module in teaching this second-semester undergraduate physical chemistry laboratory course.

Equipped with the skills and experiences from performing two previous modules in the first 8 weeks of the semester, students are better prepared to take on the more self-directed learning journey of completing this challenge module. The levels of inquiry for this module are open (level 2) and authentic inquiry (level 3). In authentic inquiry, the problem, procedures/design, communication, and conclusions are for the student to design.⁴⁶ Even for this mostly self-directed learning experience, we provide two stages of guidance.¹⁴ The first stage is to assist students in their design process by providing reading materials containing information related to the organic small molecules.^{29,30,36–38} The second stage is to engage in conversations concerning current research activities involving organic small molecules, such as their involvement in energy transfer of organisms,⁴⁷ various designs of small organic molecules,^{48–52} studies of mechanisms/properties^{53–68} for solar cell technology,^{27,69–72} the effects of aggregation of molecules on the kinetics^{73,74} and performance of technology,^{75,76} and discussions concerning the advantages of using a combination of different experimental and computational approaches.⁷⁷ Furthermore, the TA also answers any emergent questions and discusses with students any issues they may have regarding the content of their weekly journal reading. In the most recent semester (spring 2022, for example), these conversations between instructor and students occurred most often before or after the Physical Chemistry lecture class; corresponding conversations between the TA and the students occurred almost daily. As there were only two students taking this lab course in Spring 2022, the efforts spent (in terms of time and breadth) providing guidance were easily manageable. Aided by the guidance provided, the participating students developed their own tasks and a set of questions to answer.

IMPLEMENTATION, OUTCOMES, AND ASSESSMENTS

We have taught the second-semester physical chemistry laboratory course using the two-level modular approach since 2011. Our expertise in research has provided us adequate tools to face challenges related to research topics. For instance, the teaching assistant in Spring 2022 had taught both an instrumentation course and the first-semester physical chemistry lab course prior to teaching this course.

Table 1. Topology of Learning Guidance^a

type	concept	students
process constraints	restrict the tasks	able to perform and regulate the basic inquiry process but lack research experience
task overviews	make tasks visible	able to perform the basic inquiry process but lack the skills to plan
prompts	remind to perform an action	able to perform an action but may not do so on their own initiative
heuristics	remind to perform an action and suggest how to perform that action	do not know exactly when and/or how an action should be performed
scaffolds	explain or take over the more demanding parts of an action	do not have the proficiency to perform an action themselves or cannot perform the action from memory
explanations	specify exactly how to perform an action	are incognizant of the action and how it should be performed

^aNote: This table is based on ref 18 with minor modifications.

Furthermore, he had already garnered three years of research experience with using Gaussian software. This level of TA preparation was highly enabling of our approach; without it, the TA would likely have needed additional training during the previous summer. On the other hand, students taking the course this year had already used all of the instrumentation available to them through taking other chemistry lab courses in the School. This familiarity is likely important for sustaining the progress through the course and allowing students to focus on solving problems (rather than starting from square one with respect to instrument training). When considering student organization for the course, participating students are grouped in teams of two at the start of the semester (in case there is an odd number of students, a group of three is formed). As in traditional teaching of lab courses, students in a given team can complement each other's skills and thus may also generate synergy in learning, while also providing opportunities for peer learning. At least initially, self-organization is used in forming the teams (i.e., students are allowed to choose their own lab partners). In the future, we may practice grouping the students who share the same interests in choosing modules 3 and/or 4—particularly if a future version of the course is designed to span multiple chemistry subfields beyond just physical chemistry.

A successful implementation of this modular approach also depends critically on the use of proper guidance based on each student's learning abilities. Therefore, understanding of the learning levels of students and a familiarity with the topology of guidance are important aspects of teaching using the modular approaches. Lazonder and Harmsen provided an analysis of the effect of guidance on inquiry-based learning.¹⁸ Among six types of guidance shown in Table 1, we utilized a combination of them in our teaching in all stages of implementing each module. As students perform experiments as a group, the level of guidance is provided according to the higher level, even when they have different lab skills. This position is based on the assumption that a student with lesser skills (or knowledge) will be able to learn from a student with a higher level of skills, and this situation offers an opportunity for the students to participate in peer learning. Furthermore, if it is determined that both students are not sufficiently familiar with the techniques/instrument that are needed to initiate work on the module, they will be offered extra help from the teaching assistant and provided with supplemental reading/training such as a procedure of operation shown in Table S4 of the SI.

The choice of the types of guidance is based on initial assessment of students' learning abilities through a set of questions and practice problems at the beginning of the laboratory course. The questions are mostly addressed during a given lab session. The summary shown in Table 1 is helpful in

assisting instructors to determine a proper level of guidance. The insight from studying Table 1 allows one to quickly identify the type of learning guidance an instructor needs to provide. For example, students may be asked to find from the literature a method of studying protein folding process. Some would take it upon themselves to find appropriate reference materials based on the distributed lab description. When students need assistance to plan the experiments are task overviews. Students in this situation need different guidance according to Table 1. Over the past 10 years of teaching the course, nearly all of the students have been assignable to the top two types in Table 1. As can be expected, different guidance is required depending on whether a given student is at the initial stage of a given module versus the data-acquisition stage, the analysis stage, or the reporting stage. This is because different sets of skills are required at different stages. For instance, some students are quite capable of performing data acquisition but are less comfortable with scientific writing.

Although most of the guidance provided by instructors is communicated to students orally, some of it is communicated in writing—especially when harmonized guidance must be provided across multiple groups. In addition to the tips described by Quattrucci²³ and discussed above, we found the effectiveness of guidance depends strongly on the background and experience possessed by instructors and teaching assistants. Currently, fewer than 10% of instructors in the US use project-based learning in teaching.⁷⁸ The experience presented here adds to the knowledge and contributes positively to the growth of the modular approach in teaching. One of the challenges we faced a few times over the past 10 years is the breakdown of instruments during the semester. When the repair cannot be performed promptly, students are given data from previous years so that they can still perform data analysis.

Since 2011, when the first module-based physical chemistry laboratory course was offered, we have continuously invested effort to improve and develop modules and enhance implementation methods. A typical timeline of implementation of the laboratory course is provided in the SI. Through the course, students gained significant independence in planning and learned how to execute their plans accordingly. The outcomes are reflected by the detailed reports completed by the students. For instance, students need to extract equations from a textbook and the relevant reference,¹⁹ as shown in the SI, to use in their research and this skill is useful as this is the practice for a starting researcher to get information from references.

Furthermore, the results in different depth and length can be obtained by students. For instance, in the finding of types of myoglobin, student A in the report illustrated three types, i.e.,

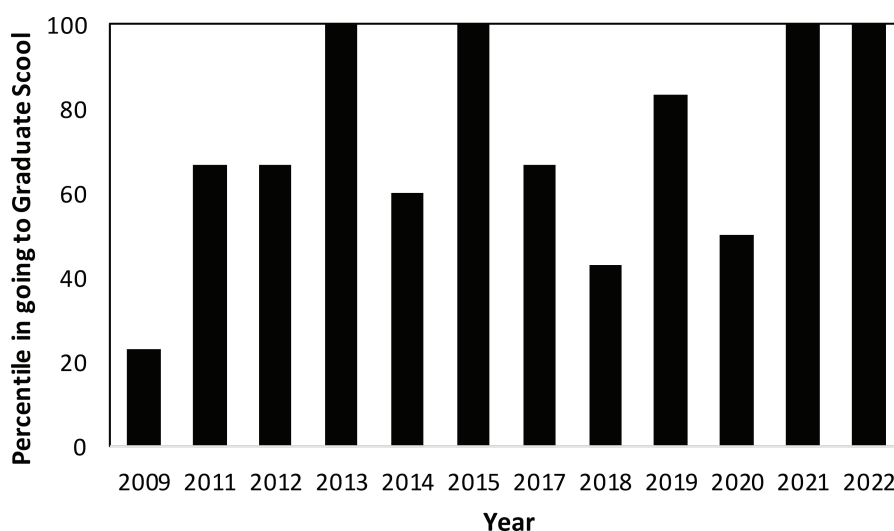


Figure 2. Percentage of students attending graduate programs after taking the lab course (and graduating) using the modular approach (since 2011), compared to the corresponding value from 2009 when a traditional lab curriculum was used. The total number of students in 2009 was 13, and the numbers of students in each of the other years are provided in Table S2 of the SI, but totaled 45.

horse heart myoglobin, sperm whale myoglobin, and blackfin tuna myoglobin. Student B reported six and student C reported five types of myoglobin. Different numbers of references are also cited, depending on students' respective efforts. At the end of the laboratory course, students provide presentations that are open to all faculty and graduate students. Questions are asked during or after each presentation. In the studies of molecules shown in Figure 1, students obtained calculated IR spectra for the singlet and triplet states. The students then analyzed the spectra, as detailed in the report shown in the SI.

The modular approach provides the setting for students to perform "research-like" experiments and gain greater in-depth knowledge in a given topic. First, they obtain background information for their efforts from reading journal articles to gain in-depth knowledge of the subject matter; along with discussions about the material with the TA, their peers, and the instructor, this aspect is meant to help transition their approach for acquiring background knowledge to more closely match the literature review of practicing scientists. Next, during their experiments, the students bring to bear different methodologies to learn about their system of interest, a step that will also help them gain greater in-depth knowledge of those methodologies—and their respective advantages and limitations. Finally, students have the opportunity to better acquire in-depth knowledge through preparing and giving their final research presentations, answering questions, and "defending" their work, as well as watching the presentations of their peers and participating in the subsequent discussions.

Each student's performance is evaluated in determining the final grade, which is composed of prelab reports (8%), lab reports (75%), an oral presentation (15%), and TA discretion (2%). Detailed guidelines of the grading standards are provided at the beginning of the semester as a part of syllabus. In addition to grades, one of the important aspects of the course is to improve critical thinking skills. Many studies and topics can be found that are relevant to the development of student critical thinking, including its definition and practices,^{79–81} systems thinking and systems maps,⁸² thinking at the molecular level,⁸³ group influence on thinking,⁸⁴ teaching critical thinking skills,⁸⁵ promoting systems think-

ing,⁸⁶ and critical thinking goals.⁸⁷ The modular approach described here provides an excellent way to support the development of systems thinking, which is a holistic way to investigate factors and interactions that could contribute to a possible outcome. Writing reports requires integrating the results from different measurements (module 1) and/or different calculations (module 2). The successful completion of the reports demonstrates that students are mastering systems thinking skills. Furthermore, increased research confidence and identifying themselves as scientists are good indications of mastering critical thinking skills. In spring 2022, students were asked to take a voluntary survey on research confidence and identification as a scientist (questions of the survey and the results are provided in Table S5 of the SI).

In addition to improving critical thinking skills, another goal of this course is to excite students to pursue research opportunities. One quantitative measurement of achieving this goal is to look at the number of students choosing to enroll in graduate programs after graduation. Figure 2 summarizes the percentage of participating students going to graduate programs since Spring 2011 after the modular approach was implemented; here, the graph also includes the data point from Fall 2009, when a group of students took the laboratory course that was taught by our previous traditional approach.

It is clearly demonstrated in Figure 2 that the percentage of students choosing to enroll in graduate programs has shown notable improvement; one must be cautious when evaluating the significance of the data set. This increase may also be due partly to the change of the course selection: Since 2011, the second-semester physical chemistry courses (lecture and lab) became elective instead of mandatory for chemistry majors in the so-called comprehensive chemistry specialization (which is most of the chemistry majors). Once provided the option, many of these students choose a different upper-level course track instead of physical chemistry. Particularly given the known rigor of the second-semester physical chemistry track, most of the students who do choose to take the track may already have some degree of interest in a research-oriented career. On the other note, the lack of more data points from prior than 2009 is another reason for caution in interpreting the results. Nevertheless, the current assessment results are

promising and continue to support to the survey that have demonstrated positive outcomes of using modular approach.^{88–92}

As a part of the School's research efforts in the area of chemistry education,^{93–95} the current modular approach can be used in the other advanced chemistry laboratory courses by adding more modules focusing on different topics. As for potential adaptations by other institutions, Module 1 can be directly used by Physical Chemistry Laboratory courses when the instruments and techniques such as NMR are available or with minor changes to adopt to their own instrumentation at institutions. Although module 2 is highly specialized, instructors can adapt it by replacing the research direction with their own.

CONCLUSIONS

In order to provide students with independence in experimental design, to help them develop critical thinking skills, and provide greater material depth, we have developed a two-level modular approach for the second-semester physical chemistry laboratory course. Implemented since 2011, the course material comprises four modules—two inquiry-based modules and two project-based modules. Students' reports and presentations over 10 years have demonstrated ample evidence for the increased higher-order thinking skills, the improved independence with respect to planning experiments, and increased interest in research activities. The assessment results provide encouraging evidence that these modules have achieved the course's goals and assisted students in choosing more research-based careers, including a high percentage of participating students enrolling in graduate programs.

Future larger-scale implementations of such modular approaches in teaching laboratory courses will allow us to collect critical data for analysis on the broader effectiveness of the approach. This work will also serve as an interesting platform for advancing chemistry curriculum changes. For instance, the modular approach described here can be further refined to allow additional (and perhaps all) advanced chemistry laboratory courses to be combined into one single course. In that scenario, the combination of the second semester physical chemistry laboratory course and (say) the advanced inorganic chemistry laboratory course would allow us to reduce credit hours while maintaining the goals of both courses while tuning the content to a given student's specific interests. Therefore, the work presented here lays a solid foundation for future efforts involving curriculum changes in undergraduate chemistry education. The project-based modules can also serve as models for developing one-semester senior project courses.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.2c01225>.

List of modules developed and their implementation details (PDF)

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Notes

The authors declare no competing financial interest.

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