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Mentoring Graduate Students in Research and Teaching by Utilizing Research as a Template

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S *Supporting Information*

ABSTRACT: We have designed a unique guided-inquiry-inspired course for entry-level graduate students using chemical research as a mechanism to teach research-oriented problem-solving skills. The course has been designed for flexibility around a shared research experience. The curriculum can be modified each year by incorporating a new research project into the framework of the course. Advanced graduate students and postdoctoral scholars serve as course instructors, providing significant teaching and mentoring opportunities for them. The benefits of the inquiry-driven approach have been reinforced through careful selection of instructors and students. We have been able to create a positive learning environment and a highly beneficial award system for students and instructors by offering an opportunity to publish class results in a scholarly journal. The course serves as a template for the implementation of similar graduate coursework at comparable research institutions.

KEYWORDS: *Graduate Education/Research, Inorganic Chemistry, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, General Public, Curriculum*

■ INTRODUCTION

The primary goal of graduate education is to prepare students as researchers for careers in either academic or industrial environments.[1] Generally, an integral part of research training at the graduate level occurs through peer-guided osmosis; namely, knowledge flows in a rather unstructured way from senior graduate students or postdoctoral associates to new graduate students. We have recently introduced a new graduate-level course to examine and augment this research training via a guided-inquiry-inspired approach. In this contribution, we outline the structure and set of methods that we have used to build a flexible and adaptive offering. We also briefly discuss the perspectives of the participants, the initial outcomes of the course, and some of the evolution the course has undergone.

Although standardized, expository laboratories are common in most entry-level chemistry courses, such preset laboratories do not satisfy the need for the high-order cognitive training required in graduate-level research.[2] Many institutions currently offer guided-inquiry-based classes to their upper division students, and some institutions have begun to adopt such classes at the first-year level.[3−7] However, the majority of existing classes have established project schemes that only skim the surface of a research experience. Consequently, students are rarely expected to independently develop a project beyond a set of historically accomplished tasks that clearly demonstrate curricular keystones.[5]

We actively utilize many of the positive aspects of inquiry[8,9] by providing a controlled environment and controlled student body to facilitate students' transitions into graduate research. Students enter our class with a well-developed knowledge of chemical principles, allowing them to effectively formulate complete hypotheses and solve chemical problems. It can be argued that students at the postbaccalaureate level are in the perfect phase of education for inquiry-inspired classes because they are not subject to the cognitive overload associated with having to learn new techniques while exploring. In addition, to maintain enthusiasm throughout the course without giving answers to students,[10] the prestigious goal of journal publication is offered as motivation. In turn, the instructors are given a chance to improve their instructional skills and lead a research group. Hence, the class provides both the students and the instructors a constructive, inquiry-driven experience that is crucial to training the next generation of researchers and educators.[8]

Historically, guided inquiry has been the basis for the majority of graduate-level education, particularly in doctoral programs. Professors, as mentors and advisors, facilitate the research of beginning students, who in turn must actively inquire about common practices and develop methods to solve novel problems.[11] As graduate students progress through their respective programs, approaching doctoral or even postdoctoral levels, they must make another transition from being the agent of exploration to the manager of others' exploration. This transition often lacks guidance and formal training. In most cases, it is assumed that the graduate will quickly transition between the role of research assistant to industrial researcher or assistant professor on the basis of proven aptitude in research. Multiple recent studies have shown that graduates are more employable, successful in their respective programs, and ultimately capable of teaching when given mentorship and opportunity to teach.[12−15] Peer-level instruction has been

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shown to be useful in the presentation of chemical laboratory information;[7] therefore, a pairing of graduate students at disparate levels has the potential to be a successful mechanism for instruction and learning for all participants.

The class's instructors are Ph.D. candidates and postdoctoral researchers with strong interests in collegiate teaching. Instructors are selected from the Center for Sustainable Materials Chemistry (CSMC), a National Science Foundation Phase II Center for Chemical Innovation. Graduate students who are generally in their first year of study are offered the class as an extension of M.S. degree programs in semiconductor processing or polymer chemistry through the Master's Industrial Internship Program at the University of Oregon.[16] These seemingly diverse programs, semiconductors and polymers, are both relevant to the field of inorganic solution processing of thin films, which is the primary focus of the CSMC.[17−22] Students enter the class with a skill set that can leverage the opportunities provided by the instructors. The course is carried out in the Center for Advanced Materials Characterization in Oregon (CAMCOR), a shared-user facility. CAMCOR contains extensive state-of-the-art materials characterization equipment, which is made available for the students.

Considering the construct, the class's primary research projects have been designed to address three major criteria. First, the class must conduct new, pertinent research. Incorporating research as a model for education is an excellent method for defining problems and developing methods for seeking solutions.[23] This method offers the challenges of learning how to approach research problems and offers "on-the-job" training for incoming graduate students with a grade and a potential journal publication as incentive. The process involves higher cognitive development and skills carrying real-world significance, which increases retention of acquired information.

Second, the class is designed to address major criteria of graduate education in materials chemistry, including characterization and synthesis. Recent work by Ellis, Widstrand, and Nordell shows this method to be promising for increasing both interest in and retention of subject matter presented in coursework.[24] Training to use necessary instrumentation for future research is incentivized scholastically and structured as a peer-based activity with review of performance and understanding. This method lessens the burden on other members of the graduate students' future research groups and offers the students an ability to report information taken from pertinent instrumentation with confidence, even as beginning researchers.

Third, the class offers students a rare opportunity to learn how to produce a journal publication as a function of coursework. This approach allows students to have comprehensive exposure to the job activities of a graduate researcher: planning, researching, and writing for publication. Early exposure to professional responsibilities has been shown to be a successful educational method.[24] Though the third criterion is a lofty goal, we subscribe to the belief that setting high goals is a precursor to student success.

■ ROLE OF INSTRUCTORS

Instructors are tasked with establishing curricula, evaluation criteria, and budgets for the class. These tasks were chosen to acclimate the future collegiate educators to their coming duties. Attention to these factors has been shown to be important in graduate preparation for successful teaching and research,[8,25,26] making this an opportunity for professional growth while enhancing employability. Students are expected to actively participate in research and laboratory activities. Faculty members within the CSMC make themselves available to provide mentoring for both instructors and students alike.

■ COURSE OBJECTIVES FOR STUDENTS

The course is designed to address six major objectives associated with the success of researchers at the graduate level:

1. Introducing the students to research-group dynamics by imitating a research-group format.
2. Exposing the students to new chemistry and technologies through guided reading assignments.
3. Using inquiry to establish standardized, best-practice laboratory standard operating procedures in small groups.
4. Exposing students to experimenting in cutting-edge, shared-use facilities.
5. Using peer review in grading of presentations and formulation of manuscripts.
6. Writing a manuscript covering the research carried out in the class.

We elaborate on each of these objectives in the following sections of the paper.

We have successfully run a course at University of Oregon based on these criteria and objectives twice. The first iteration used early center chemistries to produce nanoscale capacitive devices with tuned dielectric constants; the second iteration of the class refined methods used to produce and evaluate group 13 metal hydroxide precursor materials for solution-processing nanoscale electronic devices. Both classes have produced manuscripts, with the first currently in publication[27] and the second currently submitted.

Introducing Students to Group-Research Dynamics

Though research groups are an integral part of the graduate-level research experience, their unique functional aspects are rarely addressed in undergraduate laboratory courses. Traditional laboratory classes tend to pair students of equal experience for individual experiments that take little more than hours to complete.[2] Graduate research often involves projects shared among collaborators with diverse backgrounds for weeks, months, and even years. Productive insights, project standardization, and success of projects are typically contingent on open communication among researchers.

In this class, a "research group meeting" format is used for information exchange, which mirrors the prevalent form of communication in graduate study. Because the students come from diverse backgrounds, the approach brings beneficial insights to the surface. For instance, the first iteration of the class generated values for the morphology of thin films by X-ray reflectometry (XRR) and atomic force microscopy (AFM) that did not agree. These data were opened to inquiry-based interpretation and the students were better able to understand that XRR probes both interfaces of a film, whereas AFM only investigates surface topography. By starting each class period with a group discussion, best practices are standardized via thoughtful discussion. Daily group meetings also allow students an opportunity to defend their ideas and collectively decide how to progress by evaluating which tasks should continue and which to abandon in order to achieve the class goals. In this way, inquiry is promoted and students learn to lead when they have insights toward solutions. At the same time, the emphasis on direct experimentation emulates a true research format.

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Introducing Students to New Chemistry and Technology through Guided Reading Assignments

The class has no formal text just as true research has no formal text. Samples of pertinent literature are provided to the students as a basis for initiating a project, as lead references for an ongoing literature search, and for writing an introduction to their paper. Quizzes based upon the assigned literature are administered to ensure that the students stay up to date on required class reading and to encourage students to actively discuss the contents of what they have read. Finally, literature review offers a clear visual of what publication-quality figures are and how to use data to bolster a story. Further literature searching on the state-of-the-art is encouraged to hone the students' understanding of the context of the class's experiments.

Using Inquiry To Establish Standardized, Best-Practice Laboratory Standard Operating Procedures in Small Groups

With some literature background, students formulate hypotheses, procedures, and practices to complete the class project. There are many instances in which standardization has been necessary for group success, including but not limited to solution formulations, synthetic procedures, dilution and titration mechanisms, material separations, and characterization techniques. The group is allowed to decide how to use a limited budget to plan instrument usage and ultimately provide pertinent figures for their paper. Emulating standard research practice, the course instructors are encouraged to offer guidance about budgets and time management if the students are not advancing as necessary.

Using group discussion generates a streamlined equipment scheduling and training regimen. When given the task of deciding how much time to spend on individual and group training for facilities, the students quickly go about defining roles for themselves and taking on the associated responsibilities. Use of instrumentation is facilitated by students readily asking each other about previous training from their prerequisite polymer or semiconductor coursework and then organizing accordingly. Small group work allows for concurrent scheduling via guidance of the inquiry into training and scheduling of experiments in the shared-user facility.

Exposing Students to Experimenting in Cutting-Edge, Shared-Use Facilities

The CAMCOR facility has a variety of advanced materials characterization equipment.[28] Students have access to all equipment in CAMCOR with the only limit being the budget. Upon completion of required training, access is provided to instrument calendars, allowing students to directly schedule time for their measurements. During group meetings, the class carries out budgetary analysis to determine whether it is more cost beneficial for the class to train in a technique or simply have a trained technician do the evaluation. For instance, because of the low number of samples evaluated using AFM, students opted to have technicians provide those measurements, but the students trained to do spectroscopic precursor evaluation owing to the high volume of spectroscopic data required for the project.

As part of the standard curriculum, each student in the class is required to formulate a presentation about one of the characterization techniques available in CAMCOR. The presentations include the fundamentals of the measurement, best practices in sample preparation, and the applicability to the overall project. Grades for the presentations are assessed on the basis of responses to peer review.

Utilizing Peer Review in Grading and Formulation of Manuscripts

Unlike most conventional courses, this class features a significant amount of peer review. In a well-functioning research group, there is extensive discourse and review. Properly managed discourse among graduate students can provide for a highly productive research environment. As research centers and educational institutions, we strive to produce skilled skeptics who are capable of defending good ideas with logic and evaluating the scientific merits of others' ideas critically and fairly.

As previously mentioned, each student in the class gives a presentation about a characterization technique that is peer reviewed. Instructors also offer grades for the presentations. Criteria for grading include the following: (i) Were the principles of the measurement clearly defined? (ii) Did the presenter clearly demonstrate the applicability of the technique to the project? (iii) Would you be likely to commission this person to have these tests done on your samples?

Students are encouraged to ask questions until they feel comfortable that the grading criteria are addressed. Reviews are given anonymously. In the history of the course, only one student out of fifteen opted out of the review exercise by assigning full credit to the rest of the class despite performance. The student was later questioned about the behavior and viewed the practice of reviewing peers as being outside of the responsibilities of a student. Aside from this single student, the peer-review method rendered evaluations of presentations surprisingly similar to those assessed by the instructors (within one standard deviation). Because of the small sample sizes, it had been expected that interpersonal feelings would influence grading among students; however, we have found that not to be the case in our two iterations thus far.

Finally, participation grades for the entire course are assessed via peer review. A sample assessment rubric can be found in the Supporting Information. Each member of the class assigns numerically scaled grades to all other members of the class according to five basic criteria listed below:

1. Did the individual provide regular and pertinent input during group discussions?
2. Did the individual listen and consider the ideas of others during decision making?
3. Did the individual exhibit professionalism and respect for his or her colleagues?
4. Did the individual contribute significantly to the overall success of the group?
5. Would you seek out this individual for future collaboration?

We believe that these questions are important reflections of research performance. The most interesting anecdotal findings from this exercise are that the peer reviews consistently reflected distaste and disdain for minimally participating students. In contrast, students who worked toward their abilities, though varied, had positive reviews. Even the aforementioned student who assigned full credit to all other students on the presentation reviews docked points from the idle student in that cohort on reliability-related criteria. One of the major challenges presented to the instructors is the task of mentoring students so that they see why participation is critical not only in this class but also in their education and their future careers. It was observed that students tended to express a great deal of generosity toward their peers upon assessment, with strengths being addressed in greater numbers than weaknesses.

In the second iteration of the course, the list was appended to include a prompt for students to indicate the importance of their peers to the overall project. This change was made to generate a better, more democratic method of determining authorship for the final class paper but was not used in overall grading of the students. The necessity of this sixth prompt will be discussed later.

Writing a Manuscript about the Research Carried Out in the Class

From the beginning, the students in each class are motivated to write a manuscript covering the findings of the class. To accomplish this grand goal, students are encouraged to set up online document sharing and bibliography management. In the first iteration of the class, active writing and review were undertaken immediately by all but one member of the class. The manuscript was written, reviewed, and iteratively edited by the majority of the class and then submitted to the instructors. Instructors were then tasked with reviewing the article and providing feedback to the students. Following minor grammatical and graphical modification, the article was submitted to the journal *Solid State Sciences* and subsequently accepted for publicaion.[27]

The second iteration of the class had more stringent individual writing requirements, with each student being assigned sections of the paper to write for the instructors' review. Writing began immediately after the midterm examination was completed. Currently, a second paper is being prepared from the work of the second class, following a review process similar to that used with the first paper.

■ GRADUATE INSTRUCTOR REFLECTIONS

From teaching this class, we (the instructors) learned a great deal about research group management. Leading the group through the entirety of a research project provided a great deal of insight into team management and teaching through doing. We also learned a great deal about conflict management, as each iteration had at least one set of incompatible student personalities and relatively stressful situations to manage and overcome. Our involvement in conflict resolution, and our assistance in moving the project along, endeared us to the students. In the months since the class, it has become clear to us that we are now regarded as trusted peers and mentors by many of the participants who still seek us out to discuss data and experiments unrelated to the class.

We have found that the experience of leading this class reflects positively upon us in applications for academic positions. The initial postdoctoral instructor is currently working as an assistant professor at a primarily undergraduate institution. The initial senior graduate student enjoyed the experience so much that he returned as a postdoctoral scholar to lead a new group by teaching the class for a second iteration. After teaching the second iteration, he secured a position as an instructor at a large state school. The last postdoctoral instructor involved in the course is actively applying to academic positions and using the class as an example of his teaching and leadership abilities. Overall, this has been a quite beneficial experience that has helped us develop our teaching philosophies and instructional abilities. Upon reflection, we are all more likely to use inquiry in future instruction because of our favorable experience with intensive inquiry-based exercises and our observations of the positive value of the exercises.

Former Student Reflection

A statement from one of the former students offers a student perspective on the experience:

> *During the summer of 2010, I was one of six students who participated in the first iteration of the class. Although I had little familiarity with the class format, I felt that it was an opportunity to learn about graduate-level research and journal publication. Initially, I struggled to keep up with the frantic pace of class, project management, group organization, and the intensive research involved. After expressing my concerns to my instructors, they helped me realize that the cause of the class's struggles stemmed from a lack of leadership. As a result, I volunteered to take on the responsibility of leadership by becoming a project manager. By doing so, I began to excel, receive accolades from the instructors and my peers for my efforts. In the end, our hard work and diligence translated into a published journal article [see ref 27] despite the early struggles.*

Current Instructor Reflection

This statement from a current course instructor provides an instructor's perspective on the experience:

> *Due to my experience, I was granted the opportunity to be one of the instructors in the second iteration. As an aspiring professor, I took advantage of the opportunity to develop instructional skill that will be useful in my future career. Due to previously being a student in the class, the students were quite open and responsive to my suggestions. As the course progressed, the students began to take ownership of the project as I had taken ownership of my own, which was very rewarding to witness. For me, knowing that my guidance was having a positive impact on these students was the greatest form of satisfaction during the course. I learned a great deal from the challenges that developed during the class, particularly how to improve student−student and student−instructor interactions. Overall, my experiences as a student and an instructor in this class have allowed to me to grow academically and professionally in ways I would not have envisioned prior to this experience.*

■ EVALUATION AND EVOLUTION

The effectiveness of the course was metered through final publication as well as in-class assessments. Assessments, such as weekly quizzes, were used to keep students up to date on the literature. Although quizzes were used as a prompt for student action and as study guides for students to prepare for examinations, midterm examinations were used to determine whether students understood the experiments and the reasoning behind the research in which they were actively involved.

Midterm examinations were generated to achieve the goals of evaluating student understanding. These exams required students to generate process flows and answer intricate questions pertinent to interpreting data for their respective project. The first cohort of six students did extremely well on the processing midterm exam, with mean scores of 96% and a standard deviation of 5%. The second iteration of the class, with nine students and two midterms, had a broader-reaching project, and that fact was reflected by the lower class averages on the processing midterm ($86 \pm 7\%$). The lower average grades for the processing midterms in the second cohort likely

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are due to the greater experimental specificity of the individual students in that iteration of the class. For example, one group of students concentrated on Raman spectroscopy and another concentrated on synthesis. This led to comprehensive exams reflecting a strong understanding of the specific topic and a weaker understanding of broad application. It should be noted that with such small sample sizes and the requirement for project-specific exams, these data are correlational at best.

Because writing a research paper for a scholarly journal is a backbone of the course, assigning authorship fairly is of utmost importance. In the first iteration of the class, order of authorship was determined solely by alphabetical order. This method was problematic because it did not reflect the amount of work each student put into the project. That is to say, minimally participating students received higher billing than key experimenters and writers. The system was abandoned because it was unfair, nondemocratic, and arguably not representative of common authorship practices.

During the class's second iteration, a great deal of importance was put into rectification of the issues involving authorship. Although both iterations had significant use of peer review in the grading of the class, the second iteration used the peer-review process to generate a democratic basis for order of authorship. In the peer-review section, students were asked to rank their co-workers' importance based upon the prompt: "This individual contributed significantly to the overall success of the group." The rankings provided by the class allowed authorship to be assigned both fairly and democratically. We suggest using a similar method for those pursuing a similar course at their institution.

Issues also emerged with the writing assessment in the first iteration of the course. The paper was primarily generated by two of the students who took leadership roles. It was difficult to do a writing assessment on the other four class participants because of the level of editing that was going on between the students within the class. In the second iteration, the group meeting was used as an opportunity for the students to split the paper into sections and assign the sections to individuals. This simplified the writing assessment for instructors and also provided the students with tangible measurements of their peers for utilization in review.

Student course evaluations indicated that a majority of the class felt that the guided-inquiry experience was appropriate for their level of education. Many also indicated that the course provided their first opportunity to generate published research results. Some students equated the class to an internship-type experience for research. Anecdotal class reviews showed that students recognized the utility and philosophy of the research in both the assessment and their own reviews of the class. Generally, negative reviews were registered about time constraints, interactions with other students, and the lack of standardization. As a group, students reported having a fruitful exercise in discovery that developed skills that helped them have successful internships as researchers and engineers in companies. Two students who entered the Ph.D. program at the University of Oregon have described a smooth transition to the research environment, taking knowledge and skills from the class to advance their research projects.

■ CONCLUSIONS

This paper outlines an inquiry-based graduate course in which both instructors and students gain experience by carrying out some the roles of professors and graduate students, respectively. The instructors of the class gained valuable experience teaching at the graduate level and managing a small research group with a designated goal of their own design. Instructors also gained experience in the practical matters of generating curriculum, quizzes, tests, readings, and grades. The instructors have validated their abilities to teach and conduct cutting-edge research with a small, diverse group of students; these experiences have supported academic applications and subsequent employment. We are continuing to track the progress of the careers of both the participating students and the instructors via social networking web sites as part of a longitudinal study of the impact of the class on career choices and career trajectories.

To date, the success of this inquiry-inspired class has been directly related to the abilities, subject expertise, and motivation of the students and instructors. As evidenced previously, the class has been a useful introduction to the realities of graduate scholarship for postbaccalaureate students. It is also an excellent introduction to the academic instructional setting for circa-doctoral students who rarely have the opportunity to lead their own classes. We believe that similar programs can and should be implemented in other areas of chemistry at the graduate level. The underlying challenges that the course addresses, as well as the implemented methods, have the potential to considerably enhance graduate education. By using active apprenticeship models and learning-through-doing exercises, students and instructors are simultaneously able to learn valuable lessons about research, group dynamics, and leadership that will carry through to their chosen careers.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Table of students' peer reviews; rubric used for peer review. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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