Addressing the Millennial Student in Undergraduate Chemistry

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Foreword

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Before agreeing to publish a book, the proposed table of contents is reviewed for appropriate and comprehensive coverage and for interest to the audience. Some papers may be excluded to better focus the book; others may be added to provide comprehensiveness. When appropriate, overview or introductory chapters are added. Drafts of chapters are peer-reviewed prior to final acceptance or rejection, and manuscripts are prepared in camera-ready format.

As a rule, only original research papers and original review papers are included in the volumes. Verbatim reproductions of previous published papers are not accepted.

ACS Books Department

Editors' Biographies

Christopher R. Dockery

Dr. Christopher R. Dockery is the Assistant Department Chair, Director of the Master of Science in Chemical Sciences, and Associate Professor of Chemistry at Kennesaw State University. He has established a diverse forensic analytical research group where he has supervised 42 undergraduates and one graduate student in research. His interests cover a broad range of topics in forensic and analytical chemistry that have produced numerous publications and presentations at national and regional meetings, many with student co-authors. His projects have included an analysis of drugs of abuse, forensic analysis of dyed textile fibers, and the development of novel teaching experiments in addition to his primary research on the analysis of gunshot residues by laser-induced breakdown spectroscopy. He routinely teaches Peer Leading in Chemistry and has supervised PLTL for general chemistry 1 and 2.

Gretchen E. Potts

Dr. Gretchen E. Potts is the Director of Integrated Studies and UC Foundation Associate Professor of Chemistry at the University of Tennessee at Chattanooga. For the last 12 years, she has led an active research program supervising 21 students on diverse projects. Her research interests include forensic chemistry, environmental analytical chemistry, and bioremediation. She has given presentations on her research at the Pittsburgh Conference and National ACS. She has also presented workshops on flipping the classroom to UTC faculty, as she commonly "flips" her general chemistry and instrumental lab classrooms. She recently represented UTC at AAC&U's 2014 Summer Institute on High Impact Practices and Student Success.

Chapter 1

Millennial Students and Undergraduate Chemistry

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Millennials lead highly structured and scheduled lives where they are pushed to achieve academic and professional successes and serve the greater good of the community. Advances in technology have created 24/7 connectivity, constant multitasking, and short attention spans. However, the reliance of many educators on conventional teaching methods has failed to engage this generation. What innovative strategies are being explored to highlight millennial tendencies to thrive on technology and juggle assignments? How do we reach millennial students in deep conversations while promoting critical thinking? This book and introductory chapter explores inventive pedagogies in chemistry classrooms that build upon the millennial students' strengths and interests.

Introduction: The Changing University Environment

Those who teach in undergraduate chemistry programs face an ever-changing environment. While most public universities are still assessing students using the traditional grades, twenty-six states now assess university-success using retention figures and graduation rates, shifting to a performance funding model touted by Complete College (*1*). In Tennessee, for example, public universities compete for a pool performance funding and though not fully funded, a successful year can increase state funding a few percent, which could translate to a million dollars in support (*2*). This also means that in a very competitive year, a university could lose out on a million dollar of support.

Due to declining economics, we face reduced support for an increased classroom size. With the increase in classroom size, we ask "Is a traditional lecture the most effective method for communicating chemistry?" Perhaps not. Researchers at University of Washington are currently analyzing active learning methods across the disciplinary literature. After analyzing 225 studies, results published in *PNAS* reveal that passive learning comes in a far second (*3*). Student retention in the classroom increased with active learning, which is perhaps more relevant to the performance funding of the Complete College model.

But, if we apply active learning in our classrooms and labs, whom are we reaching? Currently, professors can find vast generational diversity in the classroom. Of course, the majority of our students are classified as the Millennial generation, born after 1981 (*4*). However, we also encounter students classified as GenX (born 1961-1981), Boomers (born 1960-1973) and even a few students who represent the Silent generation (born 1925-1942). Who do we address with the new active learning pedagogies? Is it possible to reach all of these populations of students with one style of teaching? How does one best deliver content to facilitate active learning and critical thinking? To help answer these questions we will dig deeper into the nature of the millennial student.

The Millennial Student

The millennial generation has been defined in several contexts and given several names, but the Pew Research Center describes them as the generation that has "come of age in the new millennium" (*5*). The expansion of the internet and technological innovation have both shaped this generation like none before. They are confident, self-expressive, informal, diverse, and close to their parents. Their connection to social media outpaces all other peer groups and as a result they function in "immediate realities" (*5*, *6*). In his book "The Dumbest Generation", Mark Bauerlien argues that technology provides students access to media and news from across the globe, but that they focus interactions locally and are uninterested in the bigger picture (*6*). Our millennial students expect 24/7 service and availability and are recklessly distracted by this "wonderful" technology. We face an uphill battle in reaching and engaging them.

Possibly the potential or amount of millennial engagement could be projected by a professor's millennial-character. The Pew Research Center hosts a quiz, "How Millennial Are You?" (*7*). After answering 14 questions, you will learn how you compare to the respondents of the national survey, including those comparable to your age. The editors, born in 1973 and 1978, independently completed the quiz and scored 58 and 84 respectively. If you simply filled the classroom with professors who scored close to 100 on this quiz, would it solve the current problems with student learning? It would be an interesting study to undertake, but most likely it would not cross the divide of student engagement. Understanding a student's generation should help with classroom management and could facilitate some engaged-learning, but ultimately fundamental changes in content delivery will need to be implemented in order to engage this techno-savvy generation.

This is not a new problem; the oldest millennial was 34 years old at the time of this publication and there have been numerous pleas trying to convince the "sage to leave the stage" (*8*). It is now widely accepted that traditional lecture is not engaging millennial students (*3*). Why then are we reluctant to put down the chalk and close the PowerPoint? Are the articles in the *Journal of Chemical Education* and resources presented in this book simply preaching to the choir? In the opinion of the editors, the most challenging roadblock to reform pedagogy is the significant mission creep and drastically increased research expectations placed on faculty at primarily undergraduate institutions. Other significant roadblocks to broad adoption of reform pedagogy stems from the lack of funding and increasing class sizes which result in a shift of instruction of general chemistry and other service courses to part time and non-tenure track faculty.

With instant access to information, millennial students are often "learning on demand" and can find specific content using online resources faster than searching the textbook (if they even have a textbook anymore). They don't want to wait for the faculty to cover the slide in class, or ask the faculty in office hours or by electronic communication. Unfortunately, many syllabi specifically prohibit the use of electronic devices during the lecture period. Simply put, the traditional lecture hall is far from their natural habitat. If that is the case, then what strategies can we use to reach them?

Reform Pedagogies

It is clear that simply "covering the syllabus and lecturing do not provide a supportive framework to encourage critical thinking skills" (*9*). At most institutions, recitation serves as a review period "in which students critique homework problems and complete a weekly quiz" yet "properly instructing students on how to solve problems algorithmically, does not empower them with conceptual chemistry knowledge" (*9*). To address this, reform pedagogies have slowly crept into the chemistry curriculum as pilot programs and research platforms. A general search for research articles on reform pedagogy in the *Journal of Chemical Education* yields numerous finds, including 43 articles on guided inquiry, 29 articles on peer leading, and 22 articles on the flipped classroom yet the word "millennial" is noticeable missing from these pages (*10*). Rath, *et al* note that students completing chemistry courses utilizing reform pedagogies such as supplemental instruction and peer leading "generally perform better in the supported classes, in subsequent courses in the sequence, and have higher retention rates in the major" (*11*). Anecdotal gains in retention may be linked to an increased sense of community experienced by students in supported classrooms.

Supplemental Instruction (SI) was developed at the University of Missouri-Kansas City in 1973 and is defined by the International Center for Supplemental Instruction (SI) as "an academic assistance program that utilizes peer-assisted study sessions. SI sessions are regularly-scheduled, informal review sessions in which students compare notes, discuss readings, develop organizational tools, and predict test items. Students learn how to integrate course content and study skills while working together. The sessions are facilitated by "SI leaders", students who have previously done well in the course and who attend all class lectures, take notes, and act as model students" (*12*). The stated purpose of SI is to increase retention and student grades within targeted historically difficult courses and to increase graduation rates. The successes of SI in achieving these goals have been well documented and SI has been offered internationally at an estimated 1,500 institutions impacting hundreds of thousands of students each year (*13*).

Peer-Led Team Learning (PLTL) is an active learning reform pedagogy designed to engage students in group discussion of content knowledge. Students are not expected to arrive at concept invention, rather open dialog among peers while reinforcing concepts. As such, most applications of PLTL supplement only part of the traditional lecture period, or occur in recitation or supplemental sessions. Peer or workshop leaders are undergraduate "student(s) with good communication and people skills who have done well in the course previously" and are "there to actively engage students with the materials and with each other" (*14*). Typically, students are not provided with an answer key and the sessions are graded for participation only. Students are therefore encouraged to talk about the problem freely, without fear of losing points for arriving at the wrong answer. In one editor's personal observations, a measure of success in a peer-led session is walking into a classroom to hear students actively engaged in conversation about chemistry. Independent research on retention progression and graduation rates using PLTL at two different institutions show students in PLTL general chemistry classes are less likely to withdraw than their non-peer-led counterparts (*15*, *16*). Additionally, Lewis shows PLTL classes "featured a statistically significant improvement of 15% in the pass rate for the classes, compared to conventional, lecture only classes" while maintaining "a comparable score on a comprehensive ACS final exam".

Flipped learning was first introduced by Bergmann and Sams in an attempt to help absent high school science students catch-up on missed material (*17*). The result is a pedagogical movement that engages students in active learning in the classroom and moves direct instruction into the student domain. Though "flipping" takes many forms, the key is engaging students and removing all forms of passive learning from the classroom (*18*). Perhaps flipped learning is the key to engaging the millennial generation. These students have been connected to technology since birth and struggle to be attentive for long periods of time. A flipped classroom environment could provide the alternate learning style which might best accommodate the millennial student.

In the flipped classroom, the professor does have a more hands-on role with the students and therefore in a much better space to gage student learning. The professor can then increase or decrease the rate of instruction based on this immediate feedback (*19*). Outside of the classroom, students may watch a pre-recorded lecture, videos from the internet, or even be directed to read in the lecture text. The onus is on the student to prepare for the active learning that will take place in the classroom. Student comments on flipped settings are varied. Considering the diversity in the classroom, you will always have students who will want to learn in a traditional setting. Some students have also voiced a concern that the professor does not put as much effort into the active-learning environment. What the student doesn't realize is that the change from passive to active learning in the classroom is not easy and actually requires more work from the professor. The time and effort to make the change can also be a big enough stumbling block that many professors busy with research do not move from the traditional lecture format (*20*).

Another active learning pedagogy is inquiry-based learning, which was originally developed in the sciences in the early 1980s (*21*). This pedagogy encourages students to employ the scientific method, including the development of a hypothesis, to work through new concepts and develop theories (*22*). It encourages critical thinking and discourages direct memorization of material. Also known as problem based learning (PBL), this pedagogy is popular in laboratory settings and in the classroom (*23–29*).

A specific form of inquiry-based learning used in chemistry classrooms and laboratories is termed POGIL, **P**rocess **O**riented **G**uided **I**nquiry **L**earning. POGIL applies problem based learning but focuses on group learning in a collaborative effort and relies significantly on reflection and critical thinking. The professor works as a facilitator, encouraging students in the critical thinking process and traditional lecture is abandoned. Students are allotted jobs in the group, including manager, recorder, reflector, technician and presenter (*30*). This style of active learning does fit the some of the characteristics of the millennial student, but for those prefer a tradition style, this method causes more distress. The research, however, shows it is effective. When compared to traditional lecture, students are overwhelmingly positive (*31*). More importantly, researchers measured progress in student learning, critical thinking and a reduction in attrition. As companies are looking for new employee who can think critically and work in team environments, perhaps POGIL is preparing the millennial generation for this new job market where skills are more important than the academic major (*32*). Unfortunately, due to limited resources and increasing class sizes widespread adoptions of these reform pedagogies in typical undergraduate chemistry curricula are the exception.

Undergraduate Chemistry Curriculum

As these new pedagogies are established to accommodate our changing classrooms, chemistry departments depend on the American Chemical Society Committee on Professional Training (ACS-CPT) to define the goals and learning outcomes for undergraduate chemistry programs in the United States. Established in 1936, the goals of the Committee are three-fold,

- to conduct and enhance an approval procedure for bachelor's degree programs in chemistry,
- to promote effective practices and innovations in chemistry education, and

- to promote broad participation in chemistry to enrich the profession with the talents of a diverse group of individuals (*33*).

The current CPT guidelines for approving undergraduate chemistry programs are dated Spring 2008, but the Committee will be releasing a revision in Summer 2014 (*34*). According to 2010 data from the US Department of Education published in the Digest of Education Statistics, there are over 2800 four-year Title IV colleges and universities in the United States (*35*). As of this July 1, 2014, there are 676 ACS-approved undergraduate chemistry programs. The ACS-CPT approval process is rigorous and well-respected.

In 2010, ACS-CPT published a report to guide departments in the development of excellent programs of undergraduate chemistry (*36*). In the document, ACS-CPT indicates that the curriculum and student learning should contain foundation courses, in-depth courses and hands-on laboratory experiences with modern instrumentation. Additionally, students should have opportunities for literature searching, computational chemistry and research. More interestingly though, the Committee deemed it important to state that the pedagogy should "excite students about chemistry", in addition to being challenging, engaging and "taught in a manner that accommodates a variety of all learning styles" (*36*). Are these comments on pedagogy addressing the millennial student without speaking directly to the obvious shift in the population of classroom students? The contributing authors of this symposium series will present herein exciting additions to reform pedagogy in undergraduate chemistry.

Review of Chapters

The work presented herein is not meant to be an exhaustive list of reform pedagogies, rather, our contributing authors present updates and reflections as practitioners who have adopted reform pedagogies and presented at recent national and/or regional ACS meetings, primarily the 65th Southeastern Regional Meeting of the American Chemical Society in Atlanta, GA, November 12-16, 2013. Each chapter works to address the unique challenges of teaching millennial students by engaging students in innovative, active learning strategies and/or increasing professor accessibility to the next generation.

K. D. Kloepper from Mercer University (GA) describes millennial students as team-oriented learners who prefer non-traditional lecture methods, yet convincing them to participate productively in class can be challenging. Participation strategies focused on group work and peer interactions were developed and implemented into assessment, projects, and class discussions. Incorporating intentional participation opportunities that complement the strengths of millennials improved engagement and learning.

J. P. Lee from the University of Tennessee at Chattanooga describes his experiences as an Assistant Professor within the first three years of teaching inorganic chemistry within a research active undergraduate program. The intent is to give a brief overview of what has been incorporated in the classroom early in his career to set precedent and rigor while fulfilling his desire to develop a symbiotic relationship between teaching and maintaining an active undergraduate research program. Emphasis is placed on the incorporation of group learning activities in upper level (i.e., Junior/Senior) inorganic chemistry classes in order to keep students actively engaged, and serves as an introduction for the incorporation of chemical literature as a tool to spark further interest in inorganic chemistry.

Scott E. Lewis from the University of South Florida presents the practical aspects for initiating, growing, and sustaining peer-led team learning (PLTL) in the General Chemistry class. In particular this chapter will focus on the necessity for team building and administrative support, and the supporting role of education research.

Lucille Benedict and James R. Ford from the University of Southern Maine discuss a flipped classroom model in a large lecture chemistry course. This model consists of a structured course website for content delivery, online quizzes and homework, and a large emphasis on group work and problem solving during lecture and recitation times. These course changes had a major impact on student success and retention in the general chemistry course at the University of Southern Maine. The D,F,W rates significantly dropped while the number of students passing the course significantly increased. Student responses to an end of semester survey revealed that many of the students found the course structure extremely beneficial to their learning and helped to alleviate many of the pressures (anxiety, and under-developed math and study skills) of the course.

Melissa S. Reeves (Tuskegee University, AL) and Robert M. Whitnell (Guilford College, NC) report on the development of computational chemistry laboratory experiments in the Process-Oriented Guided Inquiry Learning (POGIL) method, from the POGIL Physical Chemistry Laboratory Project (POGIL-PCL). In the POGIL-PCL framework, experiments are conducted in collaborative teams, focusing on multiple learning cycles with progressive complexity, pooling data among the entire class, and analyzing data peer-to-peer in the lab under the instructor's guidance. This structure changes the lab from a data collection site with analysis done later in solitude to a richer environment where students are partners in their own learning, fostering independent thinking, teamwork, and communication skills.

Chavonda J. Mills, Julia K. Metzker, and Rosalie A. Richards present Undergraduate Research (UR) as the cornerstone of the chemistry program at Georgia College, Georgia's Public Liberal Arts University. In a recent revision of the chemistry program's student learning goals, faculty identified UR as a high impact pedagogy for the millennial student and developed a roadmap for the integration of UR into the curriculum. Yet, despite success in developing a robust UR program, chemistry faculty encountered several challenges in sustaining the UR program and maintaining student interest. To address these challenges, they established a parallel series of cost-effective faculty and student activities, and a robust faculty evaluation system that values UR and a comprehensive study of student perceptions of UR.

C. L. Weaver, E. C. Duran, and J. A. Nikles from the University of Alabama at Birmingham share a progressive approach used to improve writing in the first semester organic lab course. Initially individual, scaffolded writing assignments combined with online peer review were implemented, succeeded by group writing assignments using a writing cycle. Preliminary results from the first three semesters are presented.

Luciano E. H. Violante, Daniel A. Nunez, Susan M. Ryan, and W. Tandy Grubbs from Stetson University (FL) integrate 3D printing in the chemistry curriculum, inspiring millennial students to be creative innovators. There are certainly positive characteristics associated with the millennial generation that should be kept in mind as educators tailor effective learning strategies for students of chemistry. Millennials typically possess a higher technological proficiency and a greater enthusiasm for using the latest digital gadgetry in comparison to their predecessors. In this chapter, Grubbs *et al.* illustrate one way to take advantage of this technological edge by incorporating 3D printing activities into the curricula. Several student driven projects are described, ranging from the creation of simple ball-and-stick models of common chemical structures to the fabrication of more realistic, space-filling models of proteins and quantum-optimized molecular complexes.

Meagan K. Mann from Austin Peay State University (TN) covers methods and techniques available to increase accessibility to professors in the broad demographic of students found in the millennial classroom. Included are ways for professors to communicate remotely with students through instant messaging services, social media, desktop streaming, and web conferencing systems.

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Chapter 2

Give Them Something To Talk About: Participation Strategies That Improve Student Learning and Engagement

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Millennial students are team-oriented and prefer non-traditional lecture methods, yet convincing the current generation of undergraduates to participate productively in class can be challenging. Common traits for Millennials include a preference for structure and an interest in building peer networks. Participation strategies utilizing structured teamwork were developed and implemented in analytical chemistry classes through modified discussions and assessment. Students spent out-of-class time on projects and attending specific seminars, both of which benefited in-class participation. Incorporating intentional participation opportunities that complement the strengths of Millennials improved their engagement and learning. These participation approaches can be adapted for large lecture classes, non-majors courses, and other chemistry disciplines.

Introduction

Many chemistry instructors have experienced at least one of the following all-too-familiar scenarios:

- Scenario #1: You carefully prepare a lecture with interesting examples that you are certain will keep your students on the edge of their seats. At the end of your lecture, you pose an open-ended question for discussion but are only met with blank stares. Did they even follow your lecture?
- Scenario #2: Your exam includes questions that you are sure give students a fair opportunity to demonstrate what they have learned. You provide feedback that includes suggestions for improvement. When you hand the exams back, you see students quickly flip to the grade as they leave the room. At the next class meeting, you want students to talk about the material they missed, but they have nothing to contribute.
- Scenario #3: You develop a thoughtful assignment that requires students to work through a tricky class topic. There is significant work required out of class, but when you ask the class to discuss project progress, students are hesitant to volunteer.
- Scenario #4: You ask students to read a journal article before class that you have selected specifically because it matches student interests and aligns well with course content. When you start the in-class discussion, eyes avoid you and no hands go up.

How can an active classroom be created if students are reluctant to participate? Research suggests that that active participation in class promotes learning more than lecture alone (*1–4*), so how do you get today's students, the so-called Millennials, talking? Modifying teaching strategies to better align with the strengths of today's students may be the answer.

Millennials often are characterized by their immersion in technology, and others have reported on technology-based pedagogies for chemistry courses, with examples including social networking (*5–7*), student-generated videos (*8*), clickers (*9*, *10*), "Google jockeys (*11*)," virtual laboratories (*12*), online discussions (*13*, *14*), and modified wikis (*15*, *16*). Another approach is to develop teaching strategies that take advantage of generational strengths and preferences (*17*). Howe and Strauss identified seven core traits of Millennials: special, sheltered, pressured, optimistic, rule-following, team-oriented, and high-achieving (*18*). While the media often focuses on negative aspects of these traits, these generalized characteristics can actually be beneficial in the classroom, particularly the latter three. Designing structured course activities that require teamwork and higher-order thinking may increase the motivation of today's college students.

Here, efforts by the author to improve the participation of Millennials in analytical chemistry classes are described. There are many aspects of a chemistry class where participation can be incorporated and adjusted to appeal to college students, including in group work, class discussions, assessment, and out-of-class events. Specific examples of how these modes have been used in sophomore-year Quantitative Analysis and the upper-level course Instrumental Analysis are provided. Suggestions for applying these participation-inducing activities to other courses, especially larger classes, are given.

Classroom Participation

Overview

In scenario #1, discussion stalled when students were prompted only at the end of lecture, while scenario #2 describes a failed attempt to get students talking about exam performance. Both situations could be improved by providing more structure to the discussions and tapping into students' affinity for teamwork. Millennials have more familiarity with group work in educational settings than previous generations of college students because of frequent high school group work (*19*), and potential employers place increasing emphasis on collaborative work environments (*20*). Intentionally incorporating peer interactions into classroom activities and assessment gives students more opportunities to participate, which increases the likelihood of productive discussions.

Group Work

There are many types of group work that have been incorporated into chemistry courses, with three common active-learning pedagogies including peer-led team learning (*21–23*), problem-based learning (*24–26*), and process-oriented guided inquiry (POGIL) (*27*, *28*). While there are differences between these approaches, they all share a common intended outcome of engaging students through active learning (*29*). Group work done during class has the dual benefit of providing students with opportunities to learn from one another while also having the instructor present as a guide, when and if the need arises. In-class group work models for students how to form appropriate study groups, and this can facilitate the formation of study groups outside of class.

Using alternative classroom techniques to traditional lecture promotes student involvement in learning, but waiting to do a group activity after a long span of lecture time, as described in the first scenario, may not be as effective as interspersing more frequent group activities (*30*). However, using group activities to cover course content often requires more time than lecture delivery alone.

The author has developed a participation strategy for Millennials that uses technical videos found on YouTube (unpublished). Despite students' immersion in technology, they still can struggle with appropriate use of internet resources for educational purposes (*31*, *32*). Although videos provide visual reinforcement of concepts, students may have difficulty with fully learning from narration and visual content unless guidance is provided to integrate the new material with previous knowledge (*33*). The video participation strategy positions short YouTube clips as the starting point for discussions and aids students in learning from both the auditory and visual components of the videos. Associated in-class work is structured to require students to summarize video content before integrating it with previously-learned information. Videos produced by scientific societies, individuals, and instrument companies all are rich sources of information appropriate for chemistry courses, but to maximize student participation and learning, care should be taken to select video clips that minimize extraneous information.

For example, when starting the section on mass spectrometry, the class viewed an introductory video produced by the Royal Society of Chemistry (*34*). The video includes explanations of the instrumentation, basic theory, and sample data. Students have some experience from previous courses with the instrument's operation and data interpretation, but they have not learned about the function of the instrument in detail. After watching the video, students are given prompts to help discuss different aspects of the video. Questions follow the order of information presented in the video and focus on the most important points such as the function and purpose of each component of the mass spectrometer. As part of the discussion, students draw the block diagram, which shows the main components of the instrument, on the board. Alternatively, students could work through handouts of the questions in small groups and then discuss the answers as a class.

The author also has utilized a number of different group activities in Instrumental Analysis and Quantitative Analysis at Mercer University. Analytical chemistry POGIL (ANA-POGIL) exercises have been used in both courses, and POGIL exercises are available for a range of disciplines and levels of courses (*35*). ANA-POGIL activities can be used to introduce a new topic or reinforce previously-learned material. Although many available exercises are intended to take full class sessions, longer activities can be divided into smaller pieces if traditional lecture is still being used. The guided inquiry nature of POGIL exercises is intended to introduce new material to students, but the activities can also be used to reinforce already-taught topics. For example, the author follows a 20-minute lecture on an overview of chromatography with the first pages of an ANA-POGIL activity about chromatography data. This excerpt takes students approximately 10 minutes to complete, and as students work through the questions, the instructor interacts with each group, listening for common errors or points of confusion. Answers are discussed as a full class, which provides the instructor with additional opportunities to correct student misconceptions about the material.

These activities also have been used by the author in larger lecture classes. ANA-POGIL activities have been used in the 70-person Quantitative Analysis course to introduce concepts. When working with a larger class, the author typically uses groups of three, as the classroom has immovable benches. Group activities are kept to 10 minutes and then gone over as a group. Typically in the 10 minutes the instructor still has time to interact with each group, just to a lesser extent than with smaller classes (<20 students).

Collaborative Quizzes and Exams

The second scenario, which describes a situation where students disregarded instructor feedback, touches on a common struggle: what do we as instructors want students to get out of exams? Quizzes and exams assess student learning and can inform both the student and instructor on individual progress and understanding. The timed, written format of tests, however, can over-emphasize memorization and limit the ability of the instructor to assess critical thinking (*36*). To improve the outcome for scenario #2, the students needed some motivation to look over the missed material on the exam. While there are some reports by others of alternative assessment strategies, including poster sessions (*37–39*), oral exams (*36*), and video responses (*40*), written examinations are still often the most practical form of assessment for chemistry courses.

The author developed an assessment strategy that combines individual and group work on quizzes to address the teamwork preferences of Millennials (*41*). These quizzes, called "stoplight quizzes," are completed in three phases: individual, group, and instructor. Each phase requires a different ink color—green, orange, and red, like a traffic light—and receives decreasing point values. After completing the quiz individually in green ink, students are placed into groups for discussion. During this time students may modify their answers in orange for half credit. Quizzes are turned in and graded by the instructor in red ink.

Students benefit from this practice in several ways. They get to teach one another, a practice that reinforces their own knowledge. Because they immediately re-examine the questions in their groups, students acquire instant awareness of gaps in knowledge. During the group phase, the instructor moves around the room to listen to the discussions without participating in them. This observation time yields valuable information not only about the class-wide understanding of material but also about individual student confidence. Over the years the author has observed situations where students may know the correct answer but are unsuccessful at convincing their peers. Likewise, the reverse situation has been observed, where students are over-confident in their wrong answer. Both situations lead to out-of-class conferences where the instructor may encourage the unconfident student or check in with the over-confident one.

The author also has used this assessment strategy as pre-lab quizzes for the 70-person Quantitative Analysis course. Lab sections were smaller (<28 students), which enabled faster distribution of quizzes and pens. For larger classes, time could be saved by having students bring their own colored pens. Questions on the pre-lab collaborative quizzes focused on the main goals and procedural steps of the laboratory exercise. Students worked with their lab partner in the orange phase, and these assigned lab partners stayed the same for the entire semester. Students reported that they felt more prepared once they entered lab because they had already discussed the procedure with their lab partner during the orange phase of the quiz. Furthermore, a majority of students recommended utilizing this collaborative assessment strategy for all laboratory courses.

Outside Activities Benefit In-Class Participation

Overview

The activities described in Classroom Participation require class time to complete, but class discussion can also be based on student efforts outside of lecture. Others have used extra assignments and activities to support class learning such as field trips (*42–44*) and service learning (*45*, *46*). The instructor described in scenarios #3 and #4 attempt to connect out-of-class assignments and readings to in-class discussions but failed to include appropriate structure or motivation for students. The next sections describe additional out-of-class activities and how they were leveraged to improve conversations in the classroom.

Scaffolded Projects

Students benefit from working together outside of class because collaboration can reinforce class concepts and build communication skills. Substituting a group project for a traditional problem set can particularly appeal to Millennials when project assignments include clear expectations, structured guidelines, and a mode for collecting feedback. Others have incorporated group work into homework and other out-of-class assignments in several ways, including group papers (*47*, *48*) and multimedia projects (*8*, *49*, *50*). Scenario #3 describes a situation where out-of-class work did not translate to in-class discussion. Building intentional checkpoints of student progress into class time can help address this, as described below.

Each semester in Instrumental Analysis several group projects are assigned in Instrumental Analysis designed to contain the structure Millennials crave while maintaining high expectations. Student groups range in size from two to four students, and the group projects always require an in-class presentation based on a produced work, such as a brochure, handout, or group-designed activity. Both the group presentation and product help reinforce scientific communication skills, and students are asked to evaluate each group members' contributions, including their own (Table 1).

Table 1. Typical questions for student group work evaluation.

1. Clearly describe your contributions to the presentation.
2. Who was the most helpful group member? Explain.
3. Who was the least helpful group member? Explain.
4. Distribute 50 points amongst your group members (including yourself). No two group members can receive the same score, and you should use whole numbers. Please elaborate as you see fit, using additional paper if needed.

Examples of group projects for Instrumental Analysis include:

- *Symposium series.* Students must discover "research experts" for a given topic and propose their own symposium series. As a group they design an advertisement that includes a symposium abstract, title, and list of individual talks.
- *Analysis design.* Students must propose sample preparation and analysis for a given analyte in a complex mixture.
- *Instrument presentation.* Groups investigate applications of a chosen instrument and prepare a teaching handout on its function and applications.

Analogous projects could readily be adapted for any chemistry sub-discipline, but the key feature that should be retained is in-class discussions about project progress. For the Instrumental Analysis projects described above, informal checks occurred at each class meeting. Each group was asked for a quick update that was shared with the class; for a class size of 15 or fewer, this can take as little as five minutes of class time. For larger classes, group progress could be assessed via an online survey or in-class worksheet. More in-depth progress updates were also beneficial. For the analysis design project, students brainstormed in class with their groups for about 10 minutes to come up with preliminary sample preparation schemes. This took 10 to 15 minutes of class time and accomplished two main goals: (1) it helped students over the initial barrier of starting the project, and (2) it gave the instructor the opportunity to interact with the students at key points of project development.

Speakers and Seminars

Integrating departmental colloquia, group discussion of primary sources related to the seminar, and other in- and out-of-classroom activities promotes critical thinking and helps put research into context for students. The synergy between the seminar, student interactions with the speaker, and the student activities helps avoid many of the common pitfalls in traditional discussions about assigned journal articles, such as those described in Scenario #4.

Class discussion in Quantitative Analysis and Instrumental Analysis about primary literature has been augmented by requiring student interaction with visiting seminar speakers who are part of departmental colloquia. There are a number of ways to bring speakers to campus, even when funds are limited. Speakers could be co-hosted by a neighboring institution or be part of a multi-stop recruiting trip for graduate programs. There are also some small speaker funds available from different professional organizations. For example, the author received funding from the American Society for Mass Spectrometry Local Area Speaker Program to bring Dr. Matthew Bush of the University of Washington to campus for a multi-part seminar (*51*).

There are numerous ways to promote effective discussion about student-attended seminars, which range in degree of student involvement and open-endedness. However, the author has found that large-group, open-ended discussions (*e.g.,* what did you like most about the seminar) generated the least productive and least inclusive class discussion. Instead, getting students thinking first individually, then sharing in small groups, and *then* discussing as a whole class promoted the most thoughtful participation. After attending the research seminar, the instructor can prepare worksheets for class that guide students through the main points of the talk. These guiding questions may cover such topics as the main results presented, details from the question and answer portion, or course-related information. For example, Instrumental Analysis students may be asked about presented data or instrumental methods, while Organic Chemistry students could discuss a presented mechanism.

Another way to provide some structure to student discussions about seminars is to ask them to generate "top" lists. Students individually write down a list of 10 items that they found to be the most significant from an attended seminar. They share their lists in small groups and then generate a revised group top five list. Finally, a master top list is generated as a class with input from the instructor. This type of discussion does not require preparation by the instructor ahead of time yet still provides some guidance to the students about what seminar information is most important. It could be scaled up for larger classes by having students near one another discuss their top five lists and then email the list to the instructor or teaching assistant. The emailed lists could then be compiled into a master list for the class and shared at a later lecture, via email, or a course management system.

The author has observed that students participate more when they have a greater connection to the seminar speaker. Connections can be facilitated through structured assignments and related discussions. For example, the seminar by Dr. Bush was preceded by two short, out-of-class assignments with corresponding in-class discussions. For the first assignment, students read the speaker's research overview and background on his faculty website and wrote a brief biographical summary. Ten minutes of the next class meeting was devoted to student discussion of the most interesting facts from the website. The second assignment was completed for the next class meeting. Students summarized a recent journal article related to the upcoming seminar, and about ten minutes of class time was spent discussing the article. Students were required to attend the research seminar, and the content was discussed at the next class meeting.

Another way to help students connect with literature and seminar material is to facilitate direct student interactions with the speaker. This can be done for any seminar by encouraging students to participate in the question and answer session following the lecture. If time permits, it is most engaging to coordinate a class visit by the speaker the day of the seminar. For example, as part of his visit, Dr. Bush attended the entire Instrumental Analysis lecture time on the day of his seminar. Rather than give a traditional lecture or additional seminar, he led a class discussion. The class was arranged in a circle of desks to facilitate more open interactions. After briefly summarizing his research, Dr. Bush talked about chemistry careers and graduate school, letting students ask any questions about chemistry careers or his research. Students already had familiarity with his research from the two assignments and related discussions, which helped enable a productive class meeting. Students later reported that they felt a greater connection to the presenter, which motivated them to learn more and, in turn, participate more in discussions.

Graded Participation

Overview

Including participation in the overall course grade provides students with a strong motivation for being more active in their own education and demonstrates the importance the instructor places on active learning (*52*). For Instrumental Analysis, participation is 10% of the overall final grade, while foundational courses may have participation components less than 5% of the total course grade.

Table 2. Rubric for daily quiz grades. Students may include + or – with their self-evaluation letter grade.

Participation rubric:
A Made thoughtful contributions in at least two participation categories
B Made a thoughtful contribution in one category; minimal in the others
C Sat attentively but had minimal contributions to the participation categories
D Came to class but is inattentive or disruptive
Zero recorded for unexcused absence
No penalty for excused absence
Participation categories: • Answer questions posed to class • Ask thoughtful and relevant questions • Participation within small group work

Self-Evaluation of Participation

In Instrumental Analysis, students self-evaluate their own participation daily using guidelines discussed at the beginning of the semester (Table 2). The participation rubric is shown as the first slide of each lecture for the remainder of the semester. This daily showing of the participation rubric reminds students of their expected contributions and the appropriate corresponding evaluation. Students are given a small, approximately 3” by 3” piece of paper, called a participation card that requires students to provide the following: (1) their self-evaluation grade for the day, (2) a brief justification of the daily grade, and (3) the name and brief explanation of the most helpful contributor for the day. There is no penalty if a student has an excused absence. These participation cards are turned in at the end of each class and read through by the instructor to check for appropriateness before entering the self-reported grades into the grade book. Grades that are too low or high are adjusted by the instructor, and the corresponding students are sent an email of explanation or request for a conference. Although Millennials are characterized by their optimism and confidence (*18*), the author more typically has to address students who are under-grading their contributions. In most years the author rarely needs to adjust the participation self-evaluation grades after the first week of class.

These participation cards could be modified depending on instructor preference. Grades could be entered as provided without any interference or the cards could be collected less frequently. Instead of daily grades, students could be asked for a self-evaluation on a weekly or semi-weekly schedule; however, the benefit of more frequent evaluation is that there is a greater likelihood of intervention in the case of low participation. More frequent evaluation also reminds students of their participation expectations and may provide a reality check on class progress.

Table 3. Representative anonymous student feedback about participation activities.

Group work:
Discussing questions/topics in groups was helpful because you can bounce ideas off of other people and there's less anxiety because it's in a small group.
[W]orking with groups to produce a presentation was helpful. We had to study the material in depth in order to teach it.
We were all faced with a problem, and we each took responsibility to figure out a solution—we bounced ideas off of each other.
[C]ompiling ideas together was helpful because it bridged the gap of information that one might have missed.
I found them all helpful, and learning things with a partner allowed me to later recall those conversations when preparing/reviewing material.
Group work is useful because it keeps us engaged and willing to think on our own with our peers.
Collaborative quizzes (lecture):
They really helped me understand the material better because my peers could answer questions that I had about the material.
[Q]uizzes felt more relaxed which is the best part, [which] helped me think more clearly.
You never want to let down a classmate when paired with them. It's not fair to them if you aren't prepared.
I wanted to know what I was talking about if I was potentially going to influence a peer's answer.
Collaborative quizzes (laboratory):
Instead of just blindly copying the lab, [the quiz] makes you really think about what it is and what you are going in to the room to do.
The main benefit is to be sure that lab partners are on the same page.
I think they could be good for any course because when you don't know something it actually gives you an opportunity to learn it rather than just relying on yourself to remember to go back and look at what you don't remember.

Student Perception

There is the concern that required participation may lead to superficial student contributions. However, this has not been the case for courses taught by the author, who has found that clear expectations that build on Millennial preferences result in highly productive student participation. The instructor's motivation for requiring in-class participation should be stated early and often. This helps students understand the purpose for this expectation, and the author has found that this helps improve student buy-in. The author includes the following rationale in the syllabus for Instrumental Analysis: "You will be evaluated on your participation in class. Active participation is essential for complete mastery of the goals of this course. Active participation means more than listening attentively; in a 300-level chemistry course, I expect that you are willing and able to make thoughtful contributions to our discussion. If you are engaged in discussions about course material, you will no doubt find the material more interesting and enjoyable, even at 9 am!" Representative feedback from anonymous student surveys is included in Table 3. Students responded positively to the participation activities described in this chapter.

Application to Other Courses

The strategies described here could readily be adapted to other chemistry courses, particularly upper-level, smaller courses. The author has used many of these participation approaches in lecture classes up to 70 students, and relevant suggestions for modifications for larger classes were described in the preceding sections. Additional challenges are introduced by much larger class sizes as it is more difficult to incorporate meaningful discussion and evaluate individual contributions. Others have incorporated discussion into large lecture classes through such creative means as sharing quiz responses with students seated nearby or using teaching assistants to guide small group discussion (*53*, *54*).

It may be challenging to use participation cards in large classes in the manner described in Graded Participation; however, using teaching assistants to help evaluate the responses could help reduce instructor workload. Personal response systems like clickers are another mode for collecting participation grades. Clickers generate instant feedback to the instructor and allow automatic grade compilation. The author has successfully used clickers in courses enrolling up to 70 students to obtain student self-evaluations about contributions.

Summary

Tailoring participation activities to the preferences of Millennial students, particularly their desire for structure and social interactions, can lead to improved class interactions. Incorporating group work into in-class activities appeals to the Millennial preference for teamwork. The activities described here—group work, collaborative quizzes, projects, and research seminars—were all modified to require significant in-class participation. Having students self-evaluate their daily contributions provides both the student and instructor with insight to student progress. Activities can be scaled up to larger classes with some creative modifications.

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Chapter 3

Engaging Students in the Inorganic Chemistry Classroom with Well-Defined Group Activities and Literature Discussions

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As the sole inorganic chemist in the chemistry department at the University of Tennessee at Chattanooga it is my responsibility to find new ways to keep the students engaged. This is the case at many undergraduate departments, and with a student population that is growing both in number and sense of privilege, finding new ways to keep the students engaged is challenging. This chapter describes efforts to address these issues through in-class active learning, literature discussions, and faculty networking. The use of an online community of inorganic chemists, www.ionicviper.org (Interactive Online Network of Inorganic Chemists-Virtual Inorganic Pedagogical Electronic Resource) will be described as an effective tool to accomplish these goals in the inorganic classroom. Interactive learning has been used to engage students in inorganic chemistry in class sizes ranging from as small as 7 to as large as 59. Specific examples will be described as well as broader impacts on both the student and the faculty member.

Introduction

Teaching chemistry in the undergraduate classroom to the millennial generation represents unique challenges. For example, two words that summarize what is needed in today's classroom in order to compete with the many

In Addressing the Millennial Student in Undergraduate Chemistry; Dockery, et al.;

distractions facing students are instant and gratification (*1–4*). The need for instant gratification is fueled, at least in part, by the fact that the millennial generation does not know a time where there was not access to the World Wide Web. Furthermore, the millennial generation can even stay connected, or online, in the classroom with cell phones, tablets, and laptops. There is interest in using electronic devices in the classroom (*5*, *6*); however, though these items have been shown to be useful learning tools, I am a strong proponent of writing and the cognitive connection made to the material during the act of writing. The question then becomes how do we keep students engaged who desire instant gratification while maintaining the rigor of the class? My goal with this chapter is to discuss the marriage of classical lecture techniques with active learning techniques in my upper level inorganic chemistry courses. This chosen hybrid method is to address both the students' desire for instant gratification (active learning) in the classroom while simultaneously maintaining the appropriate rigor (classical lecture).

This chapter will be devoted to my experience as an assistant professor within the first three years of teaching inorganic chemistry at the undergraduate level. The intent is to give a brief overview of what I have incorporated in the classroom early in my career to set precedent and rigor while fulfilling my desire to develop a symbiotic relationship between teaching and maintaining an active undergraduate research program. Regardless of field, in order to be the most effective at teaching at the university level, one must be active in research to stay current on progress. Likewise, if one is to be an effective researcher there is a natural teaching component that comes along with guiding students in a laboratory setting. Furthermore, I will discuss efforts to network early in one's career as well as utilize resources that are already available with particular emphasis on the Interactive Online Network of Inorganic Chemists-Virtual Inorganic Pedagogical Electronic Resource (www.ionicviper.org) website and network. This resource was developed to aid those teaching inorganic chemistry at the undergraduate level who both suffer academic isolation with many smaller undergraduate institutions only having a single inorganic faculty member in the department, and to aid in teaching material beyond a single faculty member's expertise (*7*). It is difficult to teach an expert level because it encompasses the entire periodic table. But, as educators, we demand of ourselves and want to deliver to our students.

Teaching Undergraduate Inorganic Chemistry

When one thinks of inorganic chemistry images of elements in period 3 and beyond and large complex molecular and extended structures come to mind. One could state that the field of inorganic chemistry is the central discipline within the central science of chemistry, as all chemistry sub-disciplines draw on principles from inorganic chemistry. Inorganic chemistry deals with the chemistry of the elements and the compounds they produce except for the hydrocarbons and their derivatives, and the American Chemical Society defines inorganic chemistry as:

> "Inorganic chemistry is concerned with the properties and behavior of inorganic compounds, which include metals, minerals, and organometallic compounds. While organic chemistry is defined as the study of carbon-containing compounds and inorganic chemistry is the study of the remaining subset of compounds other than organic compounds, there is overlap between the two fields (such as organometallic compounds, which usually contain a metal or metalloid bonded directly to carbon)" (*8*).

Both definitions are verbose and very daunting when one considers that their graduate studies were more than likely focused on one very specialized portion of inorganic chemistry, and now you are tasked with teaching an entire textbook full of diverse topics. Indeed, this challenge has been recognized by a group in the field and addressed by the development of the online resource www.ionicviper.org. The use of this website will be discussed below in a general fashion. The website development, content, and use have been reviewed elsewhere (*9*, *10*)

A second challenge that arises beyond the specific breadth of the topics covered in inorganic chemistry is the more general challenge of student population growth at the university level. The University of Tennessee at Chattanooga (UTC) is a mid-sized primarily undergraduate institution (PUI) with no graduate programs in chemistry. This distinction is important to our goals of maintaining a small class size for the students taught by research active faculty.

Inorganic Chemistry at UTC

A chemistry degree at UTC can involve a handful of concentrations, which include: BS Chemistry, BS Biochemistry, and BS Chemistry-STEM Education (*11*). While all degree concentrations require slightly different coursework, all concentrations are required to take a one-semester three credit hour course in inorganic chemistry (CHEM 3310). For the BS degree with chemistry concentration the student is required to take a second semester of advanced inorganic chemistry that is a four credit hour course with a laboratory component (CHEM 4320). The CHEM 3310 course is a Junior/Senior level course (*i.e.*, after organic chemistry and does not require physical chemistry), and since it services a larger number of students is higher in enrollment. A plot of course enrollment in both classes from 2006 – 2014 is shown in Figure 1 along with a projected data point for the Spring 2015 CHEM 4320 class as determined from current enrollment data. In Figure 1, the CHEM 3310 and 4320 classes began increasing in a linear fashion starting in 2009 and 2010 respectively. Interestingly, it appears that growth in CHEM 4320 has plateaued at 17 – 20 students, and the CHEM 3310 has dropped down from the high enrollment of 59 in 2013.

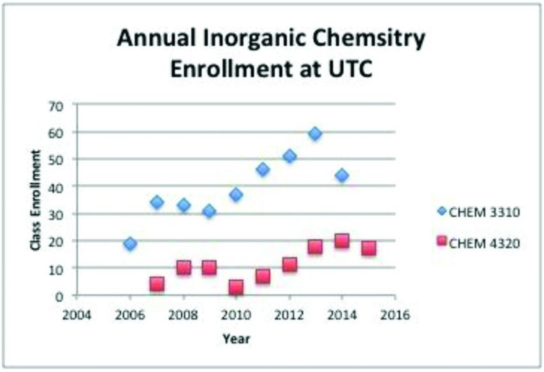

Figure 1. A plot of annual enrollment in the inorganic classes taught at the University of Tennessee at Chattanooga.

The two courses are tied to one another, but the topics covered are very different. The CHEM 3310 course builds on concepts from general and organic chemistry while the CHEM 4320 is a more traditional inorganic course. The CHEM 4320 course is considered a capstone experience for the students pursuing a concentration in chemistry as it builds on concepts taught in all four years of their undergraduate career, and requires one semester of physical chemistry as a pre-requisite. I have used active learning in both courses but for different goals. The CHEM 3310 class is relatively large enrollment (*e.g.*, 59 students in Fall 2013), and is similar in size to many general chemistry courses at smaller colleges and universities. At a 3000 level, the topics covered are not trivial, and with the greater enrollment comes more diversity in interests. Thus, I use active learning to keep the class engaged and introduce the Junior/Senior chemistry major to the chemical literature. The majority of the activities that have been utilized in class were either used from the VIPEr website or developed by me and shared on the website for others to use.

In a sense, the difference in the courses are that CHEM 3310 is a main-group chemistry course and CHEM 4320 is a transition metal chemistry course. In CHEM 3310 topics include: atomic structure and periodic trends, molecular structure with emphasis on molecular orbital theory, solid-state chemical structure, and both acid/base and oxidation-reduction reactivity. The CHEM 4320 lecture class includes topics on coordination chemistry, crystal field theory, ligand field theory, organometallics, and bioinorganic chemistry. The laboratory portion is taken as a co-requisite and builds on these concepts as well as revisits topics from CHEM 3310 such as oxidation-reduction and solid-state chemistry. Teaching inorganic chemistry in two semesters has two primary benefits. First, for higher enrollment departments it splits the number of students who need to take an inorganic laboratory, which typically requires a significant amount of synthesis. Secondly, I am able to cover a significant amount of material without feeling rushed.

VIPEr as a Resource for Teaching Inorganic Chemistry

The Interactive Online Network of Inorganic Chemists-Virtual Inorganic Pedagogical Electronic Resource (www.ionicviper.org) website and network was created by a group of inorganic chemistry faculty members at different undergraduate institutions, both public and private, across the United States to address networking in the undergraduate inorganic community (*7*). The IONiC Leadership Council administers and runs the VIPEr website where material is shared. Henceforth the website will be referred to as the VIPEr website and the online community as IONiC. Submitted learning objects are posted to the website after peer-review for other members to download and use in their own classrooms. The term learning object is used collectively to refer to an activity (*e.g.*, in-class activity, web resource, problem set, exam question, or literature discussion) where the learning goals for the class are stated first and the activity is developed "backwards" to accomplish those goals. The learning objects are shared under the Creative Commons License and can be modified and reposted to the website. For example, if one was going to start a unit on bioinorganic chemistry but has limited to no experience in that field then that faculty member could search the VIPEr website for bioinorganic learning objects posted by members. From there any number of learning objects can be used and even modified (and reposted) to fit the student population in general or the faculty member's specific goals. Following the use of a posted learning object, there is an option to comment on the learning object for what was found to work or not work in the unique scenario of individual classrooms. More recently, the IONiC Leadership Council has obtained funding through the NSF-TUES program to host teaching workshops in various disciplines of inorganic chemistry at select host universities in order to bring inorganic faculty together in person to learn more about how VIPEr can be fully utilized. In addition to a teaching resource, the IONiC community can be used for research networking as well. The Spring American Chemical Society Meeting has contained an Undergraduate Research at the Frontiers of Inorganic Chemistry symposium within the Division of Inorganic Chemistry that is organized by the IONiC Leadership Council and has been ongoing for the past seven years (*12*).

Learning Activities in UTC Inorganic Chemistry Courses

Active learning is used in both inorganic classes. In general, CHEM 3310 is more focused on group activities to build on concepts presented in class, whereas CHEM 4320 is more focused on literature related to topics presented in class. In both classes, specific examples from assigned in-class activities will be described along with an introduction and initial observations from literature discussions.

Inorganic Chemistry, CHEM 3310

An upper level chemistry course that is for majors only (*i.e.*, not a service course) and yet keeps high enrollment that rivals many general chemistry class sizes represents a paradox. This paradox is reflected in the CHEM 3310 class as can be seen in the recent enrollment shown in Figure 1. Furthermore, the high enrollment numbers come with a diverse array of interests, and, at least to some degree, it is like a 3000 level general chemistry course. Thus, I like to grab the students' attention immediately and what better way to do this in an inorganic class than with the periodic table. Poliakoff and co-workers at the University of Nottingham have assembled an excellent website where they have linked videos to each element on the periodic table where a short history of the element is given along with a demonstration of the chemical properties of the element (*13*, *14*). The students in the CHEM 3310 are informed that five minutes before every class will be devoted to the "Element of the Day Video" where we will watch a video and have a short discussion. In this way I am able to capture the students' attention immediately and with something that is relevant to the class, and as an added bonus it encourages students to arrive to class early. This teaching tool was written as a learning object and submitted to the VIPEr website under the web resources category (*15*).

It is interesting to note that as I call on a student to choose an element (I randomly pick one person each day) the typical before class chatter is immediately silenced as the group turns their attention to the video. This is important to note as the video is done five minutes before class, which is technically the students' time. Thus, I feel that these videos are an effective tool to engage the students and turn their focus to the class at hand. Furthermore, numerous student evaluations of the course indicated that they tried to get there early for the "Element of the Day Video."

Activity #1

As an introduction to the course (*i.e.*, done on the first day) the students are divided into groups and given an assignment to test their knowledge of atomic structure. Importantly, they discover that many of the questions were not covered in general chemistry, which require students to struggle and see that this course is necessary. This activity entitled "First Day Orbital Review" is found on the VIPEr website (*16*). I have used it for multiple reasons: it sets the precedent of the type of activities we will do throughout the semester, many students have the idea that this course is general chemistry III and it overcomes that idea, and personally for me I like to devote the first day of classes to something other than a lecture after course and syllabus introductions. Furthermore, this activity is a nice avenue into the first topic, atomic structure and periodic properties, and anything they were unable to answer in this introductory activity will be covered by the first exam date.

I have not assessed on this activity nor do I grade the activity. However, the overall general student interest is positive as the students immediately become active and engaged after listening to the course introduction. The final question on the activity states, "Discuss one thing your group could improve." The response to this question is almost universal with "learn more inorganic chemistry." The response is light-hearted as the atmosphere in the classroom is positive, but important as they have stated on the first day there is a lot still left to learn.

Activity #2

Throughout the semester I try to do at least one activity per unit to break the monotony of lecture. In the first unit on atomic structure and periodic properties we cover Slater's rules, which are calculations for the determination of screening constants used to find the effective nuclear charge a given electron feels, $Z^* = Z - \sigma$, where σ is the screening constant and Z* is the effective nuclear charge (*17*). Once the rules are known, the calculation is simple arithmetic; however, upon first inspection the rules are challenging because of the number of examples with different electrons in different shells and subshells shielding at varying degrees. An ideal learning object for Slater's rules entitled "Trends in Z* of 4s and 3d Orbitals in First Row Transition Metals" is available on the VIPEr website, which I utilize to make the initially obscure calculation tangible with a student-led activity (*18*). The students are divided into 6 – 7 groups and assigned a period 4 element (K – Mn) and asked to calculate the effective nuclear charge (Z*) for a 4s and 3d electron in their assigned element. As the calculation is completed the groups come to the board and plot their results in "real-time." This particular set of elements works very well as it clearly shows the 4s subshell going higher in energy than the 3d upon crossing from the s to the d block, which is to be expected since the 4s electrons are lost first upon ionization of the d-block elements. The plot also includes relative orbital energy to demonstrate that as you go across (left to right) a period, Z* increases and orbital energy decreases (Figure 2). This trend is a key concept in deriving qualitative molecular orbital diagrams in order to predict relative atomic orbital energies. This activity is not graded, and my only feedback has been anecdotal where students have stated while leaving class the day of the activity "I totally understand Slater's rules now."

Figure 2. A plot of effective nuclear charges for 4s and 3d electrons in select period four elements from the Fall 2013 CHEM 3310 class.

Activity #3

The second unit in CHEM 3310 involves molecular structure where the focus is on molecular orbital theory. At the unit's end, the students' goal is toderive "qualitative back of the envelope" molecular orbital diagrams for homo- and heteronuclear diatomic molecules, and polyatomic molecules. From their diagram, they should be able to predict simple reactivity (*e.g.*, acid/base or oxidizing/reducing agent). The method described below is taken from a qualitative approach developed by Johnson who has posted learning objects on the VIPEr website and has published the method (*19–21*). The difference that I have taken and applied to my CHEM 3310 course is that there is no introduction to point group symmetry and thus character tables are not used (the topic is revisited and covered fully in CHEM 4320). We rely on VSEPR, atomic orbital symmetry, number of nodes, and the general rule that the number of molecular orbitals must equal the number of atomic orbitals used. Thus, the molecular orbital diagram derivation relies heavily on matching orbital symmetry, and I focus on this while we are learning atomic structure. A portion of the method I have used in class is shown in Figure 3 as a series of steps. With this method the central atom valence bond orbitals are used to generate ligand group orbitals, or LGOs, (as σ-lobes) that have the same symmetry as the generator function (*19*). However, the difference in this method compared to the back of the envelope method described by Johnson is that instead of using symmetry labels to produce the molecular orbital diagram the following rules are used:

1. As the number of nodes increase, the energy of the MO increases,
2. Ligand group orbitals with the same number of nodes are degenerate, and
3. In cases where two different central atom valence orbitals (*e.g.*, s and p_z) can overlap with the same LGO, the s orbital is picked to be lowest energy because of the non-directional better overlap and the p_z orbital is assigned as partially non-bonding.

After we learn this method for predicting molecular orbital diagrams for polyatomic molecules, an in-class activity is utilized from a learning object found on the VIPEr website entitled "How Many Bonds Does PF_5 Have?" (*22*). The activity is designed for the students to determine whether or not d orbitals are required in bonding in the hypervalent molecules phosphorus pentafluoride and sulfur hexafluoride. As with the Slater's rules activity the students are divided into large groups where one group works on the phosphorus compound with d orbital participation and the other without and another two groups do the same exercise with the sulfur compound. Upon completion the groups show their work on the board in the classroom.

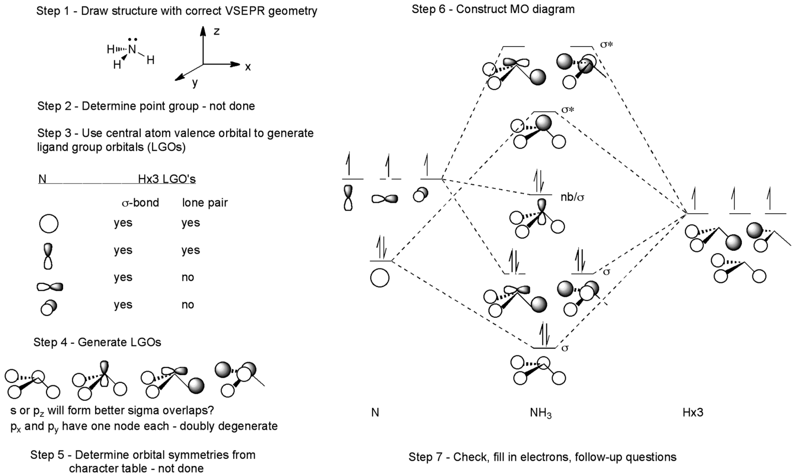

Figure 3. Steps to produce a qualitative back of the envelope molecular orbital diagram for a polyatomic molecule without using the point group character table. The example shown is for ammonia.

It should be clearly stated here that this method for molecular orbital diagram derivation is a level below that reported by Johnson and does have errors. For instance, in both ammonia and water this method does not clearly show the bonding for the p_z orbital on the central atom, and a certain degree of hand-waving is done on my part in order to explain that it is somewhere in between a σ-bonding and a non-bonding molecular orbital. A second example is for phosphorus pentafluoride where using the method described herein all three p orbitals transform as triply degenerate (they all have the same number of nodes) whereas in actuality they are doubly degenerate (p_x and p_y, E′) and singly degenerate (p_z, A_2'') when using D_{3h} symmetry and the appropriate character table. Thus, I call this method to my students the "qualitative, back of the envelope" method. However, neither of these issues cause the student to miss that ammonia is a Lewis base and that the non-bonding pair of electrons on the PF_5 molecule is localized on the fluorides of the ligand group orbitals and not the central phosphorus atom, which are key learning outcomes from these molecular orbital diagrams. To a first approximation, the results are what the student needs in order to have an "inorganic" structure/reactivity understanding of the molecular orbital diagram without using point group symmetry. One reason that point group symmetry is not taught at this level is that due to the large class size it would be challenging to teach effectively (*i.e.*, a sink or swim result would likely occur). Students in the biochemistry concentration see point group symmetry in physical chemistry II, and those students in the chemistry concentration see it twice in physical chemistry II and advanced inorganic chemistry.

Figure 4 below shows the calculated molecular orbitals of ammonia, using the computer program SCIGRESS. This and other calculations are provided to the students in order to demonstrate that their qualitative back of the envelope molecular orbital diagrams are in very good agreement with calculation. I have had numerous students state this method has helped them in physical chemistry II by allowing them to picture what the molecular orbital looks like as opposed to only describing with a symmetry label.

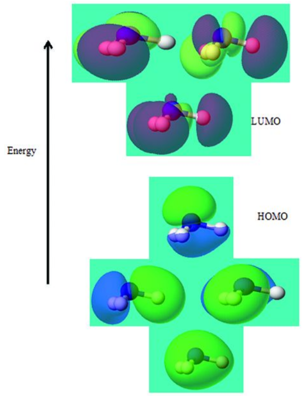

Figure 4. Calculated molecular orbitals for ammonia using Molecular Mechanics with PM3 methodology.

Activity #4

In my final example for CHEM 3310, I give the students an introduction to the chemical literature, where the class participates in a discussion toward the end of the semester. A literature discussion learning activity is available on VIPEr, which involves a paper where the research is centered on ion-exchange using hard/soft acid base theory entitled "KMS-1: The Roles of Lattice Energy and Hard-Soft Acid-Base Theory in Ion-Exchange Selectivity" (*23*, *24*). This literature discussion allows the class to apply knowledge of hard/soft acid base theory to a research result. The original published paper, along with a set of guiding questions, is assigned to the class at least one week prior to the discussion date. The students are required to answer the guiding questions and bring their responses with them to facilitate the discussion. On one hand this activity is very beneficial to the student as it gives them an exposure to the chemical literature at a relatively early stage, many for the first time, and shows them that concepts they are learning are applied to chemical challenges. However, on the other hand it is challenging from an instructor's point of view to lead a discussion with 50+ students. In particular where most if not all of whom are not at the stage where they are comfortable just talking science especially in front of such a large audience. This is atrributed, at least in part, to the fact that students do not want to be wrong, which is inherent in their nature since grade school. When exposed to something for the first time such as chemical literature that is going contain knowledge beyond their immediate grasp, there is going to be a certain degree of panic (in other words "Am I the only one that doesn't get this?"). I use this as a learning opportunity to let the students know that neither I nor any other faculty member have all the answers and when reading a paper it is okay to write questions out to yourself and search for other references to gain a deeper understanding of a concept or even a term that is unfamiliar. In other words, instant gratification is not attainable when studying science and it is okay to ask questions and be comfortable with the notion you cannot have all the answers immediately.

Advanced Inorganic Chemistry, CHEM 4320

The CHEM 4320 Advanced Inorganic Chemistry course utilizes the chemical literature heavily through discussions both developed by others and me (*25–29*). Here, I will only mention in passing the literature discussions and focus on my course introduction, symmetry unit, and organometallic unit where the latter two items extensively use in-class activities. Literature discussions include papers on coordination chemistry (*30*), an oxygen-evolving catalyst (*31*), catalytic inert bond activation (*32*), and catalytic C-C bond formation using cobalt (*33*). It is interesting to note the dichotomy that the students face with literature discussions. In order to keep the class engaged in the discussion, I assign guiding questions with the paper at least one week prior to the scheduled discussion and these are graded for completion. Even in the smaller class size (7 – 20), the students still struggle with the discussion. With the number of literature discussions we do throughout the semester the students do comment in the course/instructor evaluations. Interestingly, the students give praise that I tied topics in class to "real-world" examples. This will be discussed in more detail below in the results section.

As with the CHEM 3310 course, I prefer not to begin with a formal lecture. A short informal lecture on what I call the "seven key" inorganic molecules is given. The list is intended to show the diversity of the field. The seven molecules include: *cis*- and *trans*-tetraamminedichlorocobalt(III) as a Werner coordination compound, octachlorodirhenate(II) as a compound involving metal-metal multiple bonding, vitamin B-12 as a bioinorganic compound, ferrocene as an organometallic compound, the 1-2-3 high temperature superconductor $YBa_2Cu_3O_7$ as an example of materials chemistry, borazine as an example of delocalized bonding not involving carbon, and xenon tetrafluoride as an example of a compound containing a noble gas. I give a short history of each of these and in a sense try to "wow" the students the first day to get them excited about the course and the diversity of the field.

Activity #1

The topics of symmetry and point groups are introduced in this class with applications to group theory. These represent challenging concepts and I utilize activities/resources on the VIPEr website and an activity I developed along with lectures to introduce symmetry elements and point group symmetry (*34–36*). The concept of symmetry and molecular point group determination is given in class in lecture format, which also includes extensive utilization of the Symmetry@Otterbein University website (*37*). In addition, on the same day of that lecture a homework assignment is given for molecular point group determination that will be turned in as an in-class activity in one week. During the interim, I use a learning object from the VIPEr website entitled "Symmetry Scavenger Hunt" where the students, in groups of two, search the UTC Chemistry Department looking for objects that represent different point group symmetries (Figure 5). Furthermore, to make the activity more fun, the group that gets the most correct wins a prize. In order to complete the scavenger hunt, I setup a Google Doc presentation with instructions for picture uploading, which is shared with the class.The groups upload their photos and assign the point groups. In class, I go through the presentation to determine the correct assignments. This activity is successful when utilized prior to the molecular point group determination from their homework assignment because the symmetry scavenger hunt requires the students to "work backwards" and truly understand the symmetry elements, and then when it is time to use the point group assignment flow chart, working through the symmetry elements is more natural. Lastly, since we are interested in learning how to determine the point group of a molecule, the students are asked to complete the original homework assignment. In-class, I select students to to teach the class how they determined a specific point group using a provided oversize molecular model kit. Thus, this unit other than one and a half to two lectures is completely student led, and the results on tests and the ACS final exam are in agreement that this is an effective way to teach point group symmetry.

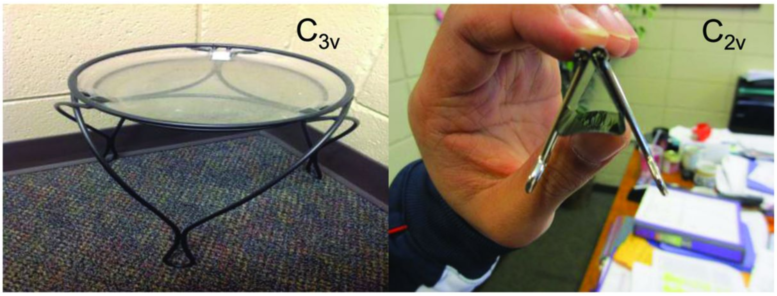

Figure 5. Example objects found by students that meet required point group symmetries as assigned in the symmetry scavenger hunt.

Activity #2

A second activity we do in the CHEM 4320 class is centered on organometallic chemistry. One of the first items taught in organometallic chemistry is the 18 electron rule (*38*), and the best way to learn something is through practice and trial and error. After completion of a ligand survey and several examples using the 18 electron rule for different complexes an in-class activity (from the VIPEr website) is given to the students. This activity entitled "18 Electron Guideline: A Primer" typically takes two lecture periods, is challenging, and asks the student to count electrons using both common methods (oxidation state and formal charge) (*39*). However, at the conclusion the students feel confident tackling any problem they are given and a significant reason is due to the ability to work together in class and teach each other while having direct instructor access as questions occur. The second activity in the organometallic section is related to the topic of catalysis. Upon completion of lectures on organometallic reaction classes, an introduction to catalysis, and the study of several homogeneous organometallic catalytic mechanisms a learning activity from the VIPEr website is used (*40*). This activity entitled "Catalytic Cycles and Artistry: Chalk Drawing 101" involves the students assigned an organic reaction along with a catalyst and asked to sketch a reasonable mechanism (without the use of book, notes, or even pencil/paper) in real-time outside on the campus sidewalk using sidewalk chalk. The activity is easily modified to fit what students are studying. For example, in the spring 2014 class we focused heavily on olefin metathesis and thus multiple olefin metathesis reactions were given for the students to determine the mechanism that ranged from cross metathesis to both ring-opening and ring-closing. There is a large activation barrier to cross to get this activity started where the student is to pick up a piece of chalk and begin. However, once complete the students are proud of their creation, they explain it to faculty and students who happen to walk by. It decorates the campus with chemistry, and doing this activity without assistance through book, notes, or even being able to sketch on paper prior requires the student to think critically about each step (Figure 6).

Figure 6. An example of a chalk mechanism for olefin cross metathesis drawn by students in the Spring 2014 CHEM 4320 class.

Results and Discussion

My background is not in chemical education, and this chapter is more focused on stories from experiences using in-class activities and literature discussions in the classroom as told through the eyes of a new faculty member. The results of these activities are primarily driven by three factors. The first is grades, and more specifically overall class average and comparison to years during heavy growth. The second metric is solicited and unsolicited student feedback where the former refers to formal class/instructor evaluations, and the latter to student comments in a non-formal non-evaluative manner (*e.g.*, via email). Lastly, and important for personal development, incorporating new teaching methods in the classroom is important for growth as an effective educator. The goal for the last point is for both the students and professor to have fun while learning as we maintain rigor and feed the instant gratification that the students desire. Though early in my career, I can easily see how if the standard lecture format is used day in and day out a certain degree of callous can be developed especially when one looks at the primary requirement of today's millennial student for instant gratification. Thus, not only is the development of new teaching techniques important to the student to keep them engaged it is also of the upmost importance to the faculty member to keep them engaged as well. Furthermore, by instituting new techniques and literature discussions in the classroom one can use their research interests to illustrate how topics taught in the classroom are used in real world applications.

One item from my teaching that has not been highlighted here is what happens in the classroom when we are not doing an activity or literature discussion. As stated in the introduction, I believe in the art of writing, and more specifically the art of note taking. In the CHEM 3310 a portion of my lecture notes are available for student download, and in CHEM 4320 no notes are available for download. The material covered in lecture is discussed in real-time as it is being written on the board for the students to transcribe into their notes. Although we think of the millennial generation as being technology driven, when it comes to what they want in a classroom I have never had a negative review on how the material in my inorganic classes is presented. Indeed, the reviews are overwhelmingly positive, and many state that I teach "old-school," which they "prefer." These comments add justification to my goals of wanting to use standard lecture techniques (or old school to quote students) in order to maintain the rigor while also incorporating active learning to address the students' desire for instant gratification.

The data in Table 1 represents the overall class average course grade for CHEM 3310 and CHEM 4320 for the past eight years (*i.e.*, since our linear growth began as shown in Figure 1). In addition, Table 1 includes the final exam score for both classes, and for the CHEM 4320 that score is specifically the raw score of number of correct questions on the ACS INORG Exam Forms 2002 and 2009. I began teaching the CHEM 4320 in 2011 and CHEM 3310 in 2012, and thus the data are limited for my teaching methods utilizing the activities described herein; however, the aim of this chapter is to describe teaching undergraduate inorganic chemistry early in one's career. Though limited, I do believe there are some general trends that can be drawn. For example, upon taking over the CHEM 3310 a very large growth was observed, and in fact the Fall 2013 class represents the

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highest enrollment in recent (*i.e.*, at least 20 years) UTC Department of Chemistry history. However, even with the observed growth and the fact that I had only taught the course for the second time the final class average remained consistent with earlier years even upon nearly doubling the number of students. One could argue that many of the techniques I incorporated kept the students engaged and not feeling like they were a number in a general chemistry course again. The CHEM 4320 grades are a little more challenging to interpret in particular the Spring 2013 class. However, what cannot be mistaken is the amount of growth observed during the years I have taught and the corresponding grade that accompanies that enrollment. The Spring 2013 grade tracks well with the fact that I had a course developed for 7 – 10 students, had only taught it twice, before jumping to 20 students. This is substantiated with the grade for Spring 2014, which shows the class average rising with 17 students in the class. Furthermore, going from year 2013 to 2014 in CHEM 4320 represent the initial institution of many of the learning activities and literature discussions and then fine tuning, respectively. The grades could represent growing pains due to how the material was presented in a 4000 level senior course between those two years. Indeed, many of the student evaluations at the end of the semester from 2013 stated that the students "were not looking forward to taking CHEM 4320" and "did not see the benefit"; whereas for 2014 the evaluations stated just the opposite the students thoroughly enjoyed the class and the activities that were done to make the material relevant.

Final exam scores are also shown in Table 1. To date, there is a limited to non-existent trend between the final exam score and the development of new teaching methods in the classroom. This is due both to limited data, and, more importantly, the fact that the enrollment in both courses is still very much a moving target. The fluctuating enrollment impacts the class as a whole and can both change the way material is presented and what can be learned from either an in-class activity or literature discussion.

It can be challenging to use student evaluations in a non-biased way as there are always going to be students who love everything you do in the classroom and those that hate everything you do. I am going to restrict my comments on student evaluations to those that specifically address the use of activities and literature discussions in the classroom, which were all positive. For example, I have received comments that addressed the question what components of the class helped you learn the best where the student answered this question using examples from our in-class activities that range from generic to specific. Several comments were stated above as anecdotal evidence for the positive experience for a given in-class activity.

The most interesting and most numerous comments addressed literature discussions. For example, comments such as "the efforts you gave to make it (class) relevant were refreshing," "Dr. Lee exposed us to literature outside of the textbook, which was very beneficial, it is nice to see the real life applications of the chemistry we learn in lecture," and "he (Dr. Lee) made it more fun when he applied the science to real world applications." I found these comments very interesting because they were in contrast to what I observed during the class literature discussions, which was uncomfortable silence. I believe that these comments show a subtler characteristic of the millennial student. This, more enduring characteristic, suggests that the students do want to be involved at all levels in their education, and apply their knowledge to solving real-world problems. However, they do not comprehend that it takes time and dedication to get to that level. In other words, the students have a lot of heart but their drive is not always present to see the task to completion. I think of this as a consequence of the desire for instant gratification, and from what I have observed so far is the biggest challenge in teaching the millennial generation. Furthermore, this trait can come across, incorrectly, as the student taking an apathetic approach to their education when in actuality what is needed is for the student to feel connected to the bigger picture.

Table 1. Class average final grades and final exam grades for CHEM 3310 and CHEM 4320 along with enrollment.

	CHEM 3310			*CHEM 4320*		
Year	***Enrollment***	***Overall class average grade***	***Final exam, class average***[a]	***Enrollment***	***Overall class average grade***	***Final exam, # correct***[b]
2015	--	--	--	16-20 expected	--	--
2014	44	--	--	17	83	33[c]
2013	59	79	72	20	71	31[c]
2012	51	79	76	11	82	33[d]
2011	46	79	79	7	89	38[d]
2010	37	80	81	7	78	31[d]
2009	31	78	77	3	88	41[d]
2008	33	79	79	10	87	35[d]
2007	34	75	72	10	89	43[d]
2006	19	81	82			

[a] The CHEM 3310 final exam is similar in nature to the ACS exam, but is a non-standardized 60 question multiple-choice exam that is given each year. The class average grade is shown. [b] The number correct out of a total of 60 questions is shown for the standardized ACS Inorganic Exam. [c] ACS INOR Exam Form 2009. [d] ACS INOR Exam Form 2002.

Future Directions

Future directions include devoting more focused attention on how a given learning activity impacts results on related final exam questions. These data could aid in my understanding of the student-learning outcome or lack thereof for a given activity. For the near future I foresee continuing to try to work on the establishment of in-class activities to support lectures and student study. This may seem like a short-sighted goal, and at least to some degree it is, but with the class enrollment still a moving target, as can be seen in Figure 1, finding the right balance with the correct number of students is challenging.

In the longer-term future, I envision taking these type activities described to another level in both classes. This would include flipping the classroom in the inorganic CHEM 3310 class and teaching the advanced inorganic CHEM 4320 class exclusively from the literature using the textbook as supplementary reading. The flipped classroom would require students to read, study provided notes, and watch recorded lectures outside of the classroom. The time in class would be used for problem solving, activities, discussions, and question/answer sessions. The desire to take CHEM 4320 to a course taught from the literature is a natural extension as the concepts in that class are readily seen in literature and the topics in the class are most in line with my research. In both the near and distant future these goals represent active learning in the classroom, which has been shown to be a beneficial method of lecture (*41*).

Conclusions

In conclusion, this chapter details an account, as seen from the eyes of an assistant professor within their first three years, for teaching the millennial generation in inorganic chemistry. Active learning was used extensively, which involved learning objects both developed by me (and submitted for others to use via VIPEr) or were used from the VIPEr website. These activities were found to be applicable to a wide range of class sizes that include anywhere from as few as 7 to as many 59 students in upper level courses. Regardless of class size the students enjoyed the in-class activities to the same degree, and were consistent in their observations about incorporating chemical literature into the classroom through group discussions. The latter item with chemical literature showed a dichotomy in my perceived opinions where during the activity the students appeared not engaged and struggled to participate. However according to the class/instructor evaluations the students appreciated the opportunity to see what they were learning applied in the real world.

The leadership required in a classroom can be daunting, and even more so with attempting to do activities in a high enrollment class as can be seen in Figure 7. Our expectation that all students will devote 110% of their time to each individual class they are taking is unrealistic. Even if this were realistic the students have grown up in an age where the answer to their question, whether right or wrong, is simply a search on World Wide Web away. This desire for instant gratification should not be construed as apathy, and cause the instructor discouragement and a false notion that the millennial generation does not care about their study habits. In fact, this desire for instant gratification should be taken as a challenge and we should rise to that challenge to meet the students' needs, while maintaining the required rigor in a university level classroom. I have chosen to address this challenge through in-class activities and literature discussions that foster a mixture of active learning and literature/"real-world" research examples while teaching the class through a standard lecture given on a whiteboard. This allows for the instructor to build on the desire of the millennial generation to be actively involved in their education while testing and improving upon their need for instant gratification. The goal is to build on the students' strength, which is heart and their desire to be connected while bringing the mindset of focus and determination up to match. Furthermore, through judicious planning one can link their teaching and research, which is an integral part for many PUI chemistry departments, and get complete fulfillment from both while focusing on one or the other individually.

Figure 7. Students in the Fall 2013 Inorganic Chemistry, CHEM 3310, course working on a group activity.

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networking between faculty teaching inorganic chemistry with the common goal of what can we do to improve student learning.

Note

For the references directing the reader to www.ionicviper.org, registration on the site may be required for access to the materials.

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Chapter 4

Starting and Sustaining a Peer-Led Team Learning Program

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National policy documents call for the need to implement evidence-based teaching practices particularly in post-secondary science, technology, engineering and math courses. This chapter presents the author's role in employing Peer-Led Team Learning in General Chemistry in the context of implementing and sustaining the reform. In particular, there is a focus on adapting the reform to the setting and efforts to build a cultural norm that is supportive of the reform. Additionally, a discussion of parameters needed for sustaining the reform, such as faculty buy-in and generating evidence of the impact of the reform are presented. The chapter concludes with a description of future directions for Peer-Led Team Learning.

Introduction

Efforts to engage the millennial student can benefit by instructors familiarizing themselves with a diverse range of instructional techniques. Similarly, documents on national policy have called for post-secondary chemistry instructors to implement alternative-to-lecture instructional practices that have an evidence base for improving student success (*1*). This chapter seeks to describe the author's role in implementing and sustaining such an instructional practice named Peer-Led Team Learning. The intended audience for this chapter is post-secondary chemistry instructors who may have an interest in implementing such a reform pedagogy. This chapter is intended to build on prior literature that describes Peer-Led Team Learning (*2*) by detailing the author's experiences in initiating and sustaining the reform. In keeping with recommendations for curricular change that emphasize flexibility of the reform, adaptability to the setting and establishing cultural norms (*3*), it is intended that this chapter will provide an additional lens for implementing effective practice. In so doing, this chapter is meant to provide the reader with the benefits and challenges of adopting reform pedagogy and discuss plausible future directions for Peer-Led Team Learning.

Peer-Led Team Learning

The instructional practice Peer-Led Team Learning (PLTL) is a nationally disseminated pedagogical reform that has been widely adopted and used in a variety of post-secondary chemistry classes (*4*, *5*). The essential feature of PLTL is to incorporate a workshop into the course instruction where students actively solve problems. Ideally, the problems are challenging and conducive to cooperation and students work in groups of 6 to 8. The workshop is led by a peer leader, an undergraduate student who has previously, successfully completed the course. The peer leader is trained and supervised to facilitate student discussion in the workshop. The faculty members teaching in the reform are responsible for training and supervising the peer leader, developing the problem sets for the workshop, and integrating the workshop activities into the other portions of the class.

An extensive amount of evidence has been collected on the effectiveness of PLTL in comparison to traditional, primarily lecture, instruction. Early adopters found that in the 18 schools where the reform was implemented, the percent of students who dropped or failed the course decreased significantly compared to historical records (*6*). Subsequent investigations reviewed in Mitchell, Ippolito and Lewis (*7*) found that implementing PLTL in a portion of the classes led to increases in common test scores or student retention over traditional lecture-based instruction, while controlling for instructor identity and students' academic background. Most of the research conducted has been performed on PLTL in General Chemistry, but evidence has also shown benefits when PLTL is employed in Organic Chemistry and Biochemistry (*5*, *7–11*).

Institutional Setting

The described work in this chapter takes place at a large, primarily undergraduate institution in the southeastern United States. The institution offers a Bachelor's of Science degree in chemistry, reports the number of chemistry majors in the hundreds (which includes many students interested in the health professions), and places approximately a thousand students in General Chemistry I over the course of a year. Class sizes at the institution range from 55 to 75 students in introductory courses and decreases in upper-level courses. The chemistry department at this setting has approximately twenty faculty members on tenure-track whose teaching loads are typically three or four courses per semester. Tenure expectations in the department require faculty to be research active with the expectation of regularly producing scholarship (e.g. peer-reviewed publications). The written guidelines do not quantify the amount of scholarship, but producing two publications in established journals would typically meet the expectation for tenure. The teaching expectations require faculty to collect evidence of effective instruction and charge each faculty member with deciding how this evidence is best collected and presented.

Initiating a PLTL Program

The first step for initiating PLTL at the setting was to establish buy-in from the administration, particularly those responsible for determining teaching assignments. To conduct PLTL at the setting, a faculty teaching assignment of one class dedicated to training the peer-leaders was requested. This course served multiple purposes: it established how the PLTL program fits into the faculty member's workload and conveyed to the peer-leaders that the skills and techniques they are learning are valuable and worth college credit along with making it clear that peer leaders were making a semester long commitment to the program. Institutional setting is a key consideration when determining how best to justify PLTL to administrators. The rationalization for the decision may include emphasizing the skill development of peer leaders or the need for active learning in the target class. Other administrators may be more interested in the actions of aspirational institutions or the potential for generating educational research from examining the impact of the reform.

The next task, and equally important, is convincing a suitable portion of faculty in one's department on the appropriateness of the reform. Faculty responses can range from an active interest to try the reform, through ambivalence or hesitancy and ending at actively opposing efforts to implement the reform. The level of faculty support needed varies based on the course targeted, with coordinated courses and those central to the major generally needing higher faculty-wide buy-in. With little faculty buy-in, the reform may still be possible by targeting courses that receive less departmental attention such as service courses for other departments or implementing the reform only in those courses that one teaches. However, there are benefits to having multiple faculty willing to try the reform. First, it supports the justification of the peer leader training course as it can support implementation in multiple classes, second, having a group of faculty committed to trying the reform can serve as a proof-of-concept to the ambivalent or hesitant faculty.

With sufficient support for starting PLTL, efforts can turn to logistics. Planning out how much class time will be dedicated to the workshop, how many points will be established for students attending or participating in the workshop and how they will be assigned, and where the workshops will be held should be decided first. In the setting, PLTL was implemented in one-third to two-thirds of the General Chemistry classes, usually involving two to four different faculty members. One of those faculty members was also responsible for the peer leader training course and overseeing the student sessions. The classes involved met on Mondays, Wednesdays, and Fridays for 50 minute sessions, and the Friday sessions were reserved for the peer-led component. Attendance and participation at the sessions represented approximately 12% of the overall grade and students could miss two or three sessions (depending on the number of Fridays in the term) without a penalty. The problem sets students work on were created by the instructors who taught the classes. Each week the instructors met and developed the problems jointly. The importance of the weekly meetings was multi-faceted as the meetings served to: ensure that the worksheets represented the content and depth that matches the instructors expectations, promote regular discussions about the content in the curriculum and relative importance of topics, and establish a cultural norm where instructors regularly reflected on and discussed means for improving the educational setting.

After establishing the parameters for the workshops, recruitment of peer leaders can begin. Peer leaders can be identified through faculty recommendations, examining course records for high performing students or those who have been active as tutors or teaching assistants on campus. The first set of peer leaders is particularly challenging to recruit as they are unfamiliar with the program and a case will need to be made for why they should join. Early in the implementation at the setting, peer leaders were interviewed and selected based on their expressed interest in working with others and their communication skills. Later, as the program grew, interviewing peer leaders became problematic and instead interested students were accepted provided they had earned at least a grade of a B in the target course. This growth coincided with the need to place two peer leaders in a room (discussed later) which served to ameliorate concerns about individual peer leaders.

Adapting the reform to the setting became essential in other aspects of implementation as well. First, it was quickly found that placing students in groups of six to eight as recommended led to some students not participating. This could be a function of the problem sets created, the room layout, or student background, but it was found that group sizes of four offered a more active setting for all students. Second, the recommendation of one peer leader per group was found to lead to excessive scaffolding of the problems by the peer leader, in some instances with the peer leader working the problems for the students. Assigning three to four groups of students to a peer leader provided sufficient numbers where the peer leader could facilitate the session without scaffolding. It also facilitated expanding the program to work with a large number of students by raising the student to peer leader ratio. Other settings will likely require a different set of decisions which emphasizes the importance of the flexibility of the reform and adapting the reform to a particular setting. Additionally, by viewing the reform effort as a guiding philosophy for teaching, rather than a set of rules to abide by, honors the instructor's autonomy and offers creativity of instruction which is essential to maintaining teaching as a rewarding profession.

Training Peer Leaders

The first peer leader training session is unique in that it serves to introduce the peer leaders to the program. The first session can begin with presenting the philosophy behind the program and emphasizing the desire for students in the course to become independent science thinkers through active learning. This serves to discourage any tendencies that peer leaders may have toward lecturing during the sessions. Next, present the general expectations for peer leaders, stressing the need for responsibility and professionalism when in the classroom. For professionalism, peer leaders need to be aware of the importance of avoiding criticisms of the instructors, other peer leaders, students, or the course materials. The peer leader indirectly serves as a representative of the institution, meaning their opinions in the setting may be construed by students as the opinion of the university or carry weight in setting course policy. The importance of peer leaders' responsibilities, such as arriving on time, can be emphasized again in terms of the impact on students' impression of the course and institution.

In addition to emphasizing the expectations for peer leaders it is also necessary to discuss the resources and support that is available to them. First, peer leaders can be made aware that the primary purpose of the training session is to prepare them for working with students. Along this line, peer leaders should feel free to communicate with the faculty leading the session and in particular conveying any areas of confusion in the materials discussed. Second, peer leaders should feel free to present any issues or concerns with their sessions to the faculty. In our implementation of PLTL, peer leaders were required to take attendance in the session and could also mark off the attendance for the rare student who was clearly unwilling to participate. Attendance was confirmed by a sign-in sheet that students were made aware they had to sign. Peer leaders were told that as long as they stayed within the guidelines established, the faculty would stand behind the decisions peer leaders made. For more serious issues, such as a disruptive student in the session, the peer leader was only responsible for reporting it to the faculty as only the faculty have resources, such as the threat of an academic misconduct report, to adequately address such issues.

Subsequent peer leader training sessions can emphasize content and facilitating the peer-led sessions. Conducting the training session as a mock peer-led session offers a nice ability to emphasize both the content and pedagogical aspects of the intended goal. In this technique, peer leaders are put in groups of four and given the problem-set for the upcoming session with the students. The faculty leading the training will then model the peer leader, visiting each group and reviewing the group consensus for each question. To ensure content understanding, the faculty member requests explanations from peer leaders. Additionally, the faculty member can ask for alternative explanations from peer leaders, pose alternative explanations for the peer leaders to evaluate and challenge the peer leader to find a reference material (e.g. the textbook) that supports their explanation.

While the faculty member leads the training session, there are also opportunities to step out of model peer leader role and point out pedagogical decisions that were made. For example, after requesting an explanation from different members of one group for the first few problems, the trainer can point out to the peer leaders that this was done explicitly to make sure that each peer leader was called on to provide an explanation. Other techniques include: requesting explanations for answers that are correct to avoid the tendency to only question students' answers when they are incorrect; have a group send a representative to check with other groups to discover incongruences or consensus across the room;

or asking peer leaders to identify what mistakes they believe students may make on the problem set.

The training course also includes the evaluation of peer leaders. Fundamentally, the course is designed to aid peer leaders in conducting the peer-led problem-solving sessions. Observing the peer leaders in action during their sessions with the students provides the most direct measure of the peer leader's preparation. Peer leaders are informed that observations will focus on areas the peer leader has direct control over (e.g. movement around the room, requesting student explanations and requesting students remain on task) and not student directed actions (e.g. students ignoring requests to remain on task). If possible, the observations can be set-up with a before-and-after design where peer leaders are observed early in the semester and given feedback, then observed again after a few weeks and evaluated on their ability to incorporate the provided feedback into their sessions.

Additional forms of evaluation that have been found to be helpful are to require a reflective journal from the peer leader where they perform self-evaluations on their role in the session. With a large program, this provides insight where regular observations are not always possible. Additionally, peer leaders can be charged with conducting an observation of another peer leader and providing feedback. This serves to share best practices among peer leaders and the evaluation can be conducted on the quality of feedback provided. Finally, as responsibility is a major point of emphasis, this can be incorporated into the peer leader evaluation as well. Points can be established for arriving to the training session and problem-solving session on time and prepared which conveys to peer leaders the serious nature of these requirements. Additional discussion of training techniques including underlying rationales for decisions made can be found in Roth, Cracolice, Goldstein and Snyder (*12*).

Sustaining a PLTL Initiative

Once past the initiation phase, sustaining a PLTL program can take advantage of momentum in that many of issues discussed in starting the program have already been addressed. Additionally, as the program becomes known to students, recruiting for peer leaders is easier and many students will begin inquiring about how they can serve in that role. Sustaining the PLTL program does face logistical challenges though and again it is necessary for the reform to be flexible to adapt to changing circumstances. For example, the PLTL program that was initiated placed 12 to 16 students in a room with a single peer leader, taking advantage of classroom space that was available on Friday mornings. Eventually, there was insufficient rooms available to continue this arrangement, so the program adopted 24 students in a room with two peer leaders. This maintained the student to peer leader ratio as well as many of the essential features: the peer leaders were still conducting the session and the students were still actively engaged in a cooperative learning environment.

Additionally, teaching assignments can pose logistic problems as well. For example, the faculty member who trains the peer leaders may receive a teaching schedule which does not allow this person to lead the training class. Ultimately, faculty buy-in becomes essential to a sustainable reform. Having multiple faculty experienced and ready to train peer leaders and oversee the program allows the flexibility to adapt to obstacles that arise from semester-to-semester and can avoid faculty burn-out by rotating the responsibility among a set of faculty. To promote this widening of expertise it would be recommended to have interested faculty co-teach or visit the training class early in the implementation.

Another consideration for sustainability is in justifying the continued institutional investment in the program. At the very least the institution is dedicating a portion of a teaching assignment for peer leader training. While some of the benefits, such as witnessing active learning happening in courses with large class size and the leadership development in peer leaders, are anecdotally apparent, these benefits may not be compelling to all. It is also recommended to incorporate efforts to collect valid and representative data on the impact of PLTL. For example, measuring student performance on a common exam can provide information on maintaining rigor in the curriculum. Measuring pass rates compared to classes without the reform or historical precedent can provide information pertinent to student retention and progression. These efforts can also serve as research findings which may support a publication, further justifying the role of the reform.

As an example, in our implementation, PLTL was run in approximately one-third to two-thirds of General Chemistry I classes offered each semester. After two years of maintaining records on the course, it was evident that the pass rates in classes with PLTL were higher than those without by a margin of 68% versus 53% (*9*). The performance on the common final exam was comparable, the PLTL classes were 1% higher than the control. The difference arose from the withdrawal rate, where the students in PLTL were less likely to withdraw compared to the classes with traditional instruction. Normally, one would expect that retaining students who were likely to withdraw would lower the class average on assessments. The student performance on the common final indicated this was not the case; so the most plausible conclusion was that the reform led to greater student success for a wider proportion of the enrolled students while maintaining rigor in the course. The benefits in increased pass rates were true for each student group, but more so for groups which were traditionally underrepresented in the sciences as defined by the National Science Foundation. The results are shown in Table 1 which is adapted from a publication on the effectiveness of the reform (*9*).

These results show not only an improved pass rate but a far more equitable pass rate across student groups with the PLTL teaching. Other areas for research could focus on the impact of the program on peer leaders or on faculty perceptions of student learning. For example, previous research has shown that peer leaders self-report long-term gains in learning and people skills as a result of their experience as peer leaders (*13*).

Table 1. Pass Rates of Student Groups

Race	***Traditional*** *Percent Passing (N)*	***PLTL*** *Percent Passing (N)*
Asian & White	55.0% (876)	66.0% (421)
Black, Hispanic & American Indian	47.0% (185)	64.7% (68)
Male	55.8% (574)	68.6% (264)
Female	51.4% (735)	63.7% (358)
Overall	53.3% (1309)	65.8% (622)

Future Directions for PLTL

Curricular-Wide Adoption

PLTL offers a unique set-up that facilitates active learning and can easily scale-up to large class sizes that are common in many post-secondary institutions. Research has shown that it is effective in promoting student success in a variety of chemistry classes. Most research has focused on the class that PLTL directly targets but research has also begun on looking for longitudinal impacts of the reform. At the research setting, for example, a cohort of students who enrolled in General Chemistry I any time across three semesters (Fall 2010, Spring 2011 or Fall 2011) was established to examine future enrollment trends (*14*). During these three semesters there were 10 classes that used PLTL and 16 classes that used traditional instruction. The future enrollment in the general chemistry, organic chemistry and biochemistry courses for this cohort were collected through Summer 2013 and are presented in Table 2.

Table 2. Impact of PLTL in General Chemistry I on Enrollment

	PLTL in GC1	***Traditional GC1***	***Differences in Percent***
Initial General Chemistry I Enrollment	555	889	
General Chemistry II	330 (59.5%)	398 (44.8%)	14.7%
Organic Chemistry I	161 (29.0%)	177 (19.9%)	9.1%
Organic Chemistry II	106 (19.1%)	124 (13.9%)	5.2%
Biochemistry	29 (5.2%)	28 (3.1%)	2.1%

The higher student retention in General Chemistry I clearly impacts enrollment in General Chemistry II where nearly 60% of students from PLTL in General Chemistry I enrolled, compared to roughly 45% of students in traditional instruction. The difference in enrollments between cohorts steadily decreases in follow-on courses until the Biochemistry course features a much reduced difference of 2.1%.

This observed reduction in differences in percent is a factor of the normal student attrition throughout a curriculum. For instance if only 50% of students from one course take a follow-on course, the difference in percent enrollment would be reduced by 50% between the original and follow-on course as well. For a reform teaching such as PLTL to influence the number of graduates it would need to offer a higher progression rate (percent of students who decide to enroll in the next course) from one course to the next than traditional instruction. This is an unlikely outcome. Instead, considering the research literature has shown that PLTL has improved student success when implemented in General Chemistry, Organic Chemistry and Biochemistry (*5*), evaluating a curricular wide adoption where PLTL is implemented in a series of courses offers the potential to find a meaningful way to improve the retention of students and the number of students graduating in chemistry.

Flipped Classes and PLTL

Flipped classes have received considerable attention recently as a means for bringing active learning into the classroom. The central premise of a flipped class is to present some of the class content in an online format either through video recorded lecture or finding appropriate, existing online material to direct students to. As students come to class previously introduced to the content, class time is freed up to explore the content in more depth. This exploration can take the form of in-class discussions, student group work or exploring additional resources. The majority of discussion regarding using flipped classes centers around the K-12 class where a small class size facilitates the in-class active learning component. Post-secondary adoptions of flipped classes in the research literature appear centered on class sizes of less than 50 students (*15–17*). However, at many post-secondary institutions, introductory courses have class sizes of 100 students or greater. Implementing active learning in these courses poses a particular challenge as time per student is necessarily reduced.

PLTL offers a potential solution as it facilitates active learning in large classes. This solution works particularly well for instructors considering PLTL but are concerned about the coverage of content if class time is dedicated to the problem solving session. Through the online presentation of content in the flipped model, concerns over content coverage are somewhat remediated. Combining flipped classes and PLTL also maintains the essential features of PLTL including ensuring the problem solving session remains an integrated part of the course.

Cyber Peer-Led Team Learning

Cyber Peer-Led Team Learning (cPLTL) has been recently developed to incorporate PLTL into an online learning experience (*18*). Like the use of flipped classes, this also takes advantage of the rising ease in substantial communications in an online platform. cPLTL employs software designed for online collaboration to facilitate interactions from student to student and student to peer leader. Research has found mostly positive but somewhat mixed findings from early adoption of cPLTL (*18*). First, the gains in student performance and limiting withdrawals with cPLTL were comparable to that observed with the conventional in-person PLTL. Second, the student discourse in cPLTL showed a higher rate of discussing problem solving techniques versus an emphasis on comparing answers in conventional PLTL. However, cPLTL was not as successful in promoting student performance among students from groups traditionally associated with a higher risk of not succeeding, namely, students from low income or from racial groups that are traditionally underrepresented in the sciences. Given that this evaluation considers an early adoption of this technique, there is strong potential for successfully incorporating PLTL into an online learning environment and this appears to be a ripe area for future research.

Conclusions

In summary, implementing a reform initiative such as Peer-Led Team Learning requires the dedicated efforts of a faculty member, is greatly supported by faculty and administrative buy-in and requires flexibility to adapt the reform to the institutional setting. Sustaining the reform requires continued adaptation to changing logistical demands and personnel. Collecting data on the effectiveness of the reform, particularly over multiple semesters can support sustaining the reform, particularly in justifying to administration the resources dedicated for the reform. Finally, future directions of PLTL emphasize the adaptability of the reform, particularly in light of the growing availability of online communication tools.

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Chapter 5

Flipping Crazy: The Large Lecture Flipped Classroom Model at the University of Southern Maine

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While the flipped classroom model has really taken off in high school and smaller undergraduate classrooms, it has been slow to develop into a model that can be utilized in a large lecture classroom. Starting in the fall of 2012 we decided to “flip” the general chemistry classroom at the University of Southern Maine (USM). By creating YouTube videos and assigning online pre-class quizzes, we were able to move much of the content delivery outside the classroom. A classroom response system allowed us to quickly gauge the level of student understanding of the assigned material, and to focus on problem areas. Online homework, a Google+ community, and a new course web space provided additional student support. During the first year, we found we were able to have students work in groups, complete more practice problems, build problem-solving skills, and have more in-depth class discussions. While these changes made appreciable improvements on student engagement and learning, we realized many students were still unsuccessful in the class due to underdeveloped math and study skills. In the second year of the flipped classroom, we added a recitation session with undergraduate teaching assistants, focusing this extra hour on math, study, and problem solving skills. These course changes had a major impact on student success and retention in the general chemistry course at the University of Southern Maine. Our D, F, W rates significantly dropped while the number of

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students passing the course significantly increased. Student responses to an end of semester survey found that many of the students found the course structure extremely beneficial to their learning and helped to alleviate many of the pressures (anxiety, and under-developed math and study skills) of the course.

Introduction

For as long as anyone in our department can remember, the General Chemistry course at the University of Southern Maine (USM) has been plagued by low success rates. Historically, only 50% of the students who enroll (and have not withdrawn from the course within the first two weeks) would complete the first semester with a grade of C- or better. Rather than place the blame on our students' abilities, or worse, accept it upon ourselves, we moved towards a drastic change in the course structure, content, and content delivery by flipping the classroom. The flipped classroom model also helped us to address the fact that within our courses we have a very diverse student population of millennial students, 1st generation, working parents, commuters, working full-time, and minority students. The flipped classroom model allows students with all types of demands in their lives to interact with the course content in a way that works with their changing lives. In the following sections, we describe some of the changes made, as well as discuss our findings and the exciting prospect of increasing retention and student success.

The general chemistry course (CHY 113) at USM is considered a service course, one in which over 95% of the students enrolled are non-majors. Three sections of the course are offered each year, with sections capped at 120 students. Two sections are available in the fall and one section in the spring, and (with rare exceptions) each section is taught by a different instructor. The lecture meets for 2.5 hours each week; a laboratory experience is provided, but is a separate course that is loosely tied to the lecture material. Given a choice between morning and evening sections in the fall, traditional millennial students tend to fill the morning section, with the evening section attracting older, nontraditional students who work full time and have significant family obligations.

Beneath the surface diversity of our students, there is a common layer of anxiety. Understandably the course has a formidable reputation and, in many cases, represents the final hurdle to overcome before fame and fortune is bestowed upon them at graduation. Many students suffer from math anxiety; you can see the blood drain from their faces when you mention the emphasis the course places on mathematics and problem solving. These anxieties are well-founded. Despite having met USM's standard for math proficiency, some students still lack useful algebraic or trigonometric skills. It is not uncommon to encounter a nontraditional student in the evening section who has not seen a logarithm in this century. The idea of using mathematics outside the mathematics classroom is a connection that most of our students fail to make, and for them the chances of changing a word problem into a meaningful mathematical problem - never mind solving it - are negligible. Ironically most of the students are quite confident of their study skills.

Student success has also been hindered by the course content. The first semester general chemistry historically followed the traditional approach where the course began with the description of atoms and molecules, followed by a quantitative treatment of mass and energy changes in chemical reactions, and then a discussion of inter- and intra-molecular forces. This logical (from the instructor's point-of-view) progression appears to the student as almost 700 daunting pages of densely packed text containing upwards of one hundred specialized terms and definitions, a handful of ad-hoc rules (and a boatload of exceptions), and thousands of examples meant to clarify but too often perceived as separate topics and algorithms to be memorized. We know from the results of standardized exams that students will only retain half of this material long enough to get through the final, and our experience in upper level-courses tells us that "through the final" sums it up pretty well.

We adopted the flipped classroom model because we knew it would allow us to put an increased focus on math and problem solving skills. However, while the flipped classroom model has been successfully employed in many smaller classroom settings (*1–3*) it is not as easy to implement in a large lecture course because of the group work that is typically involved. Providing content delivery via online videos gave us time in class to assess our students' understanding of the material, and provide further clarification where needed. This also opened up a significant block of time that could be used for additional problem solving practice. Our students could watch the videos whenever it was convenient and as often as desired. We knew how beneficial group work could be, but also had experience with the difficulties involved in successfully implementing group activities in a large lecture hall (*4*, *5*). To overcome these obstacles we employed 4 teaching assistants (TAs) per course section to aid in group work, and added a recitation session devoted to group work aimed at building student confidence and developing historically weak skills.

Things We Have Tried

Inspired by a 1999 article by Farrell *et al.* (*6*), we substituted guided inquiry group work for lectures in the fall of 2003. Students were expected to come prepared to class, having read the appropriate portion of the text. "Lecture" then consisted of students working in groups on guided inquiry activities we developed, while the instructor circulated among the groups answering questions and fostering small discussions.

Students were highly engaged in the process of their education, which is a nice way of saying that they protested vehemently over the lack of lecture time "covering" the material. By mid-semester both instructors had agreed to spend a portion (25-50%) of the time giving traditional presentations of the material. Scores on the standardized end-of-semester final exam were no worse than in previous years, and we had shown it was possible to implement small group activities in a large lecture hall setting. The instructors did not fare so well; student course evaluations lambasted the process and the instructors. We value our student feedback (as do the folks who make promotion and tenure decisions)

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and so we decided to return to a more traditional format. Nevertheless, occasional group work has become one of our most effective instructional tools.

In 2004, with support from the Maine Mathematics and Science Teaching Excellence Collaborative (MMSTEC), we added an optional Peer Led Team Learning (PLTL) (*7*) component to the general chemistry course. Students were encouraged to join a PLTL group which met weekly to work problems in small groups under the leadership of Peer Leaders, who were students who had completed the course and been trained in facilitation techniques. Students received a pass/fail participation grade from their PLTL leader that was worth 10% of their course grade if and only if it had a positive effect. (Specifically, if we let G represent a student's grade as determined from all non-PLTL sources, then students who passed the PLTL component were awarded a course grade of 0.9G+10. Everyone else received the original course grade of G.)

Participation in the PLTL program averaged around 40%. As this was a self-selected group, it is difficult to assess the impact of the PLTL program. The students most likely to participate were those who needed it the least, though there were certainly some who recognized that they would need all the help they could get, and having 10% of their course grade based on attendance was worth the effort. Students who attended the PLTL sessions did better in the course than those who did not, but we could not attribute this solely to PLTL. Survey data did show that students generally viewed the PLTL program as helpful.

The PLTL program lasted three years on MMSTEC funding (2004-2007) and then ran into funding issues. In 2011 a modified approach was begun using Noyce scholars (*8*) as PLTL leaders. Not as many students participated in this round of the PLTL program, possibly due to the limited times the Noyce scholars had available to facilitate the workshops.

In the summer of 2012, we decided to flip the classroom, and prepared a series of short (10-20 min) YouTube videos covering the topics of the first semester course. Students were expected to view the lecture videos before the class met for further discussion and practice, and were required to complete a pre-class quiz through an online homework system. Instructors usually began the class with a short informal assessment of student understanding using clickers. The course website (described below) was redesigned to clarify assignment types and dates.

In the spring of 2013 we abstracted the "chapter outcomes" from the text and generated a five page document listing over 100 goals of the first semester course. Recognizing that the "mile wide and an inch deep" nature of general chemistry is a significant barrier to student success, the chemistry department met to review these outcomes and came up with a proposal to eliminate roughly 25% of them. This proposal was circulated among the various departments served by the course, and a general discussion among the stakeholders took place in the early summer. The revised list of outcomes were then associated with course "units" closely associated with the text chapters.

The Refined Flipped Model

The current model incorporates many of the ideas discussed above. The classroom is flipped - lecture videos and pre-class quizzes are completed outside of and prior to arriving in class, while class time is used to build upon concepts, clear up misconceptions, foster in-depth discussions, and solve problems, often working in groups. The flipped classroom model helps to better prepare students for active learning experiences in the classroom; we also added a (required) one-hour weekly recitation section that follows a PLTL model to give them more time on task. Homework and quizzes are administered through an online homework system. Finally, the course website presents a unified organization of these resources. Figure 1 illustrates the relationship between the various course components, each of which will now be discussed in detail.

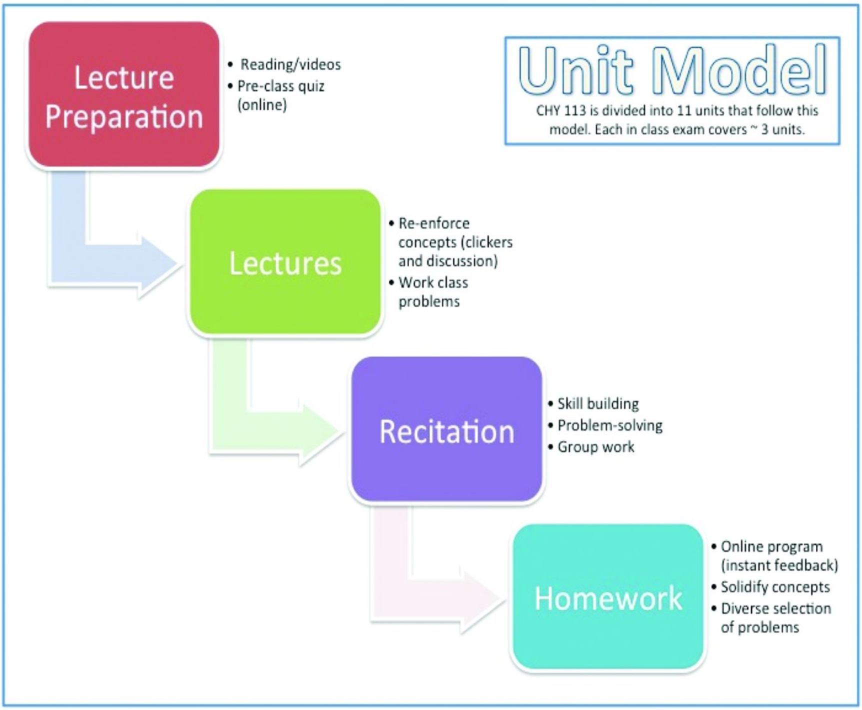

Figure 1. Unit model that was followed in our large lecture flipped chemistry classrooms. Each unit covered a chapter, or series of chapters, that focused on a content theme.

Lecture Preparation

While there were a large number of videos already on YouTube covering general chemistry topics, creating our own videos allowed us to tailor the material around the topics we wanted to incorporate and emphasize in the course. Furthermore, we believed that seeing their own instructors in the content videos was important for the students. Using screen capture software we prepared 44 short videos, each tackling a specific concept. For example, when covering stoichiometry we created one video discussing mass relationships, two related to limiting reagents, two covering percent yields, one focused on concentration, one for pH, one discussing aqueous reactions and titrations, one with an in-depth titration calculation, and a student-made video discussing indicators. Most of these videos are 10-20 minutes in length and contain numerous examples of how the concept is used. These videos have been posted on YouTube and are available for students at any time. During the fall 2013 semester alone they were each viewed an average of 150 times by our students

Students are required to complete an online quiz prior to class in order to assess their preparedness for the class, and to help them identify areas of the material they have questions on. These quizzes consist of selected problems from the online homework system, generally chosen for simplicity as well as relevance. Many of the quiz problems give the students a step-by-step guided environment of how to work the problem. Incorrect answers trigger a detailed explanation of how to solve the problem, followed by another chance to get the correct answer. In both the homework and quizzes, unlimited attempts are allowed.

Lectures

Class time (2.5 hours/week) is used to reinforce concepts and provide an opportunity to practice applying them. A typical lecture starts with a brief presentation summarizing the topic under consideration and then launches into a series of problems that students have been exposed to in the lecture preparation phase. Students respond individually to these questions using a classroom response system. This system allows the instructor to quickly determine where more explanation is needed. This question and discussion time typically lasts for half of the lecture, allowing most students to successfully apply the concepts to a few problems and ask questions on concepts or problems they find challenging. The remainder of class time is often spent in either discussion (putting the topic in perspective, discussing related current events, presenting the history, etc.) and/or providing additional opportunities for practice in small groups. The lecture section of the course provided an excellent opportunity for our students to assess and build on their skills individually.

Recitation

In the fall of 2013, we added a mandatory recitation section. Each recitation session meets for an hour each week and is modeled on PLTL lines: students work in small groups (3 or 4 students/group) on prepared, usually guided inquiry type activities that we have chosen to address particularly difficult topics or commonly deficient skills. In the PLTL model, peer leaders - upperclass students who have already taken general chemistry and been trained in facilitation techniques - keep the groups on track, and through Socratic dialog gently guide progress. Budgetary considerations force us to depart from the traditional PLTL model that provides a dedicated peer leader for every group. Instead, the 120 students assigned to each recitation section are divided into 4 cohorts of 25-30 students each, and each cohort is managed by one teaching assistant (TA) who circulates among the smaller groups within his or her cohort.

In addition to providing guidance and support during the recitation sessions, our TAs also work as tutors for the general chemistry course. All of the TAs receive tutor training through our campus learning commons. In the past, our general chemistry students have not made full use of available tutors, but this year we had more tutors available and they were completely booked. It seems reasonable that the TAs' interaction with the students in the course helps to reduce the fear some students have of seeking out a tutor. We also encouraged our TAs to share their general chemistry experiences, study tips, and academic life experiences with the students.

The first few recitation sessions focus on math and study skills. The first recitation session centers around an activity entitled "How to Use Your Calculator", in which students learn if they really know how to use their calculators as well as they thought they did. We walk the student through the process of entering numbers in scientific notation, since more than half do not use the EE key but rather multiply by 10^x, a key sequence that does not always give the same results. The activity illustrates this with selected problems. Other common difficulties that are addressed include order of operations and parenthesis, radians vs. degrees, and the change sign key. These skills are reinforced with some problems that sneak in a little algebra review.

The second recitation session deals with Study Skills. Before the study skills session students are required to complete a reading guide for the first section of reading in the textbook for the semester. During the face-to-face recitation, students work in groups and discuss the good and bad points of the reading guide and devise a plan for studying for the entire semester. Also in this session, the TAs share their experiences in chemistry and science courses and give helpful tips and advice to their cohort.

The third recitation session focuses heavily on dimensional analysis and starts to weave in chemical concepts that are being taught in the lectures. Again, this session utilizes group work to foster critical and creative thinking. The remainder of the recitations focus on topics that typically cause difficulties for general chemistry students. During each session we try to tie in the skills that were taught in the beginning of the semester.

Group work is a major component in the recitation section, and plays a big role in the lecture as well. We found throughout the course that not only did the group work create a positive learning environment for our students, it also created small communities among them. Creating a feeling of community in a large lecture can be a very difficult task, but it can help to decrease student anxiety and increase student success.

Homework

Homework is assigned through the online homework package from end-of-chapter problems that provide a good mix of the type of problems we are interested in. This reinforces the concepts from the units and gives the students a chance to apply skills they have learned in lecture and recitation. Homework problems are generally due a week after the end of the unit.

Website

We felt it important to present our millennial and non-traditional students with 24/7 access to the course content, schedule, resources, and quiz/homework program. The website provides a critical organizational tool. The home page (https://sites.google.com/a/maine.edu/chy113-blank/) presents general announcements, but the key element is the navigation menu on the left side. Content is organized around "units". Each unit (https://sites.google.com/a/maine.edu/chy113-blank/unit-4-chemical-reactions) contains a list of objectives and a table of tasks, with due dates, that must be completed for that unit. Tasks consist of readings from the text or other sources, videos to watch, and links to quizzes and homework assignments.

Effort

Flipping the classroom is not a trivial undertaking. A significant one-time effort must be made to create the videos, develop the recitation materials, select appropriate problems for the pre-class quizzes, and build the course website. Many prospective classroom flippers seem most daunted by the videos, but this was by far the most enjoyable part of the process. We did not set unreasonably high production standards and were able to record most videos in one take. Preparation for each video probably averaged around 10-15 minutes; in total, video production took less than 30 hours. We were fortunate to have a history of doing group work in the classroom and therefore had a number of worksheets readily available for use in recitation. Aside from the math and study skills sessions, suitable group activities are often available with the course text, so this effort may be minimal. We had also been using an online homework system prior to flipping the class, and it was not difficult to develop the pre-class quizzes within that environment. The course website was done using Google Sites. Once we had a page template, each unit was easily added. Apart from the initial tasks mentioned, maintaining a flipped classroom is no different from maintaining a traditional classroom, often involving little more than changing the due dates for assignments.

Results

Table 1 presents exam scores and success rates (percentage of students receiving C- or better, out of the total number of students enrolled at the end of the add/drop period) for the past 3 years of the fall sections. 2011 represents a more or less traditional approach, lectures in class with some group work and an option to participate in a PLTL group. 2012 is the first year of the flipped classroom, where most of the content delivery occurred via YouTube videos, and class time was used for discussion and group work. In 2013, we reorganized the website, reduced the course content, and added the recitation component. Hourly exams in 2011 and 2013 were essentially identical. In 2012, we used a different testing format, so this section of the table is left blank.

Table 1. Exam scores and grades for CHY 113, 2011-2013.

	Benedict 2013	*Ford 2013*	*Benedict 2012*	*Ford 2012*	*Benedict 2011*	*Ford 2011*
Exam 1	81	74	-	-	64	58
Exam 2	74	69	-	-	53	44
Exam 3	76	74	-	-	60	53
Final	40	39	37	36	37	36
Percent W	13	5	24	18	21	22
Percent D,F	16	24	35	40	42	33
Percent A,B,C	84	76	65	60	58	67
Overall success (%)	74	72	52	51	48	55

We were naturally excited to see the 15 point improvement in Exam 1 scores, but realized this could be a fluke. When Exam 2 showed 20-25 point improvement, we knew we had something. Exam 3 convinced us that we had at least taught our students how to take our tests. With bated breath, we scored the final and were quite happy to see a nearly 3 point improvement (out of 70 questions), despite having reduced the course content by 25%. The icing on the cake was a 20 point improvement in the success rate (Table 1), driven in no small part by an astounding drop in the number of W's.

At the end of the fall 2013 semester, students were asked to complete a survey about various aspects of the course. 109 students responded, 70 from the morning (millennial) group. The average student attended about 90% of the lectures and recitations, completed approximately 90% of the online homework, read slightly more than 80% of the assigned readings, and watched about 80% of the course videos. Attendance and online homework statistics are supported by clicker responses and the homework grading system; the self-reported value of 80% for the course videos is probably somewhat high, based on the number of views per video as reported by YouTube. Obviously there is no independent check on the readings, but both instructors strongly believe students arrived in class much better prepared than was the case with the traditional classroom.

86% of the students responding to the survey felt that the course improved their problem solving skills, 89% believed their math skills (as applied to science) had improved, and 72% reported improvements in their study skills. Nearly 60% recognized that these skills helped them in other classes throughout the semester.

Many of these students also participated in an end-of-semester survey at the end of CHY115, the second semester of general chemistry, in which they reported that these skills learned in CHY113 were even more helpful in other classes.

Students were asked to rate the helpfulness of various aspects of the recitation sessions (Table 2). With respect to the content of the recitations, the general problem solving activities and worksheets that constituted the majority of the recitation time was considered most helpful (98% positive), followed by exam review sessions (93%), math skills (87%), and study skills (73%). Eighty-three percent of the respondents felt group work was beneficial; this category overlaps the above. Interaction with and instruction by the course TAs was rated very highly at 95% positive. Students in the Spring 2014 CHY115 survey, asked to reflect again on some of these components of their CHY113 course, gave essentially identical responses.

Table 2. End of semester CHY113 survey results (Fall 2013, N=109), content of recitation sessions.

	Extremely	*Very*	*Helpful*	*Not Helpful*	*Percent Positive*
Problem solving activities/worksheets	49	33	25	2	98%
Exam review sessions	48	31	21	7	93%
Math skills sessions	29	27	37	14	87%
Study skills session	21	23	32	28	73%
Interaction with the TAs	52	32	20	5	95%
Instruction of the TAs	40	35	26	7	94%
Group Work	31	26	30	18	83%

Most students felt the pre-class quizzes, online materials, and readings helped them prepare for class (75%, Table 3). Two thirds of the students finished with a heightened interest in chemistry, while 60% reported a decreased fear of the subject. Eighty-two percent would recommend the course to others who need to take CHY113.

At the end of the survey, students were asked to comment on the overall course structure. Responses were overwhelmingly positive, with several students indicating that they were taking the course for the second time and found the changes to be very helpful. The TAs received universal praise, and one student remarked on how the study skills recitation had changed the way they studied for all their science courses. One student commented, "All of the different learning devices used in this class (clicker questions, quizzes, homework, videos, reading, lectures, worksheets, group work, etc.) made the course conducive to all types of learners and especially helped someone like me, who loses focus quickly, to stay engaged."

Table 3. End of semester CHY113 survey results (Fall 2013, N=109), course structure.

	Strongly Agree	*Agree*	*Neutral*	*Disagree*	*Strongly Disagree*	*Percent Positive*
Having pre-class quizzes helped me to prepare for the class so I could be an active participant in the lecture	47	32	12	9	5	75%
The online materials and readings helped me prepare for the lecture	52	27	16	7	2	76%
This course heightened my interest in chemistry	35	35	22	6	6	67%
The structure of this course decreased my fear of the subject matter	28	34	28	8	6	60%
I will recommend this course to fellow students who need to take CHY113	49	36	10	4	5	82%

Conclusions

We believe that this approach owes its success to many factors. Adding an extra hour of contact time - and one in which practical application of the concepts is the primary activity - certainly improved our students' abilities to solve problems. Giving students multiple tools to access content (textbook, videos) outside of class, and forcing them to engage with the material BEFORE coming to class, allowed instructors to tailor their teaching to areas which were most beneficial. Finally, the website provided an essential organizational tool.

While the flipped classroom model has really taken off in high school and smaller undergraduate classrooms, it has been slow to develop into a model that can be utilized in a large lecture classroom. In this chapter, we discuss our flipped classroom model in the context of a large lecture chemistry course. This model consists of a structured course website for content delivery, online quizzes and homework, and a large emphasis on group work and problem solving during lecture and recitation times. These course changes had a major impact on student success and retention in the general chemistry course at the University of Southern Maine. Our D, F, W rates significantly dropped while the number of students passing the course significantly increased. Student responses to an end of semester survey found that many of the students found the course structure extremely beneficial to their learning and helped to alleviate many of the pressures (anxiety, and under-developed math and study skills) of the course.

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Chapter 6

New Computational Physical Chemistry Experiments: Using POGIL Techniques with *ab Initio* and Molecular Dynamics Calculations

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A framework for physical chemistry experiments in the POGIL (Process Oriented Guided Inquiry Learning) method is applied to the development of two computational chemistry experiments. Each experiment focuses on developing student understanding of a concept that receives considerable exposure in previous classes: the nature of a valence electron (through molecular orbital calculations) and the significance of short-range forces in the properties of a liquid (through molecular dynamics calculations). The experiments further focus on developing process skills that are important as students transition from the physical chemistry course to graduate school or industry employment. These experiments are designed to be accessible to instructors with few resources or computational experience. Testing of these experiments with the authors' students and with faculty in workshops demonstrate an interesting set of lessons, from how students approach the experiment and their learning of the techniques and concepts, to how instructors adapt to the use of tools that are outside their sphere of knowledge.

Introduction

The POGIL-PCL project (*1*) fosters the development, implementation, and adoption of physical chemistry laboratory (PCL) experiments in the POGIL

In Addressing the Millennial Student in Undergraduate Chemistry; Dockery, et al.;

(Process Oriented Guided Inquiry Learning) framework (*2–4*). To that end, the project has four objectives:

- Write physical chemistry laboratory POGIL experiments with coverage of the major subdisciplines of physical chemistry, including thermodynamics, kinetics, quantum mechanics, and spectroscopy.
- Promote professional development of faculty who teach physical chemistry lab courses.
- Create a sustainable community of physical chemistry lab instructors to support development and adoption.
- Develop workshops to support the other objectives.

We describe here the development of computational chemistry experiments in the POGIL-PCL framework.

Structure of POGIL-PCL Experiments

The structure of a POGIL-PCL experiment is shown in Figure 1 and has been described in detail elsewhere (*1*). This starts with an experiment title that is a question to be studied. That question leads to a series of "data-think" cycles. Each cycle begins with pre-experiment questions that have students initially explore the system to be studied and review experimental protocols. These questions are often based on prior knowledge of chemical systems or experimental techniques that students are to apply to the current experiment and therefore connect to the exploration part of the learning cycle. Examples include the significance of intermolecular forces in phase transitions or methods for preparing solutions of known molarity and desired precision.

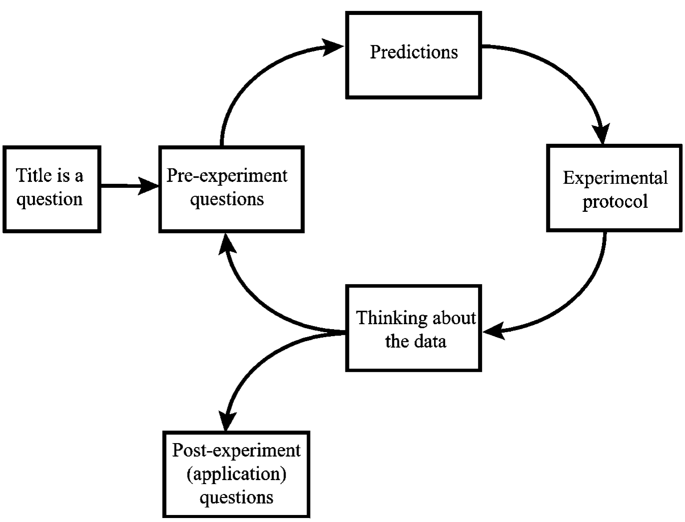

Figure 1. Schematic of POGIL-PCL experiment structure. (Reproduced with permission from reference 1. Copyright 2014.)

Based on information provided in the lab materials and answers to the pre-experiment questions, students make predictions about experimental outcomes. The purpose of these predictions is twofold. First, they help students develop expectations of what they will observe when they do the experiment. Rather than just waiting for the instrument to give them a value, students instead begin to consider ranges of reasonable values and why results might fall outside of those ranges (such as incorrect reasoning in the prediction or faulty experimental design or implementation). Such experimental design is one way in which the concept invention part of the learning cycle is incorporated into the POGIL-PCL structure. Second, as has been shown with the use of demonstrations in science lectures (*5–7*), student learning is improved when making a prediction before observing the result, even if their initial prediction is substantially incorrect. The act of comparing their observations to their predictions assists students in overcoming their original misconceptions about the chemical system.

Students then perform experiments and obtain data. The POGIL-PCL lab materials include a general protocol, but students are expected to make decisions about experimental design during the course of the experiment, and to do so with the expectation that the class data will be pooled in order to obtain a richer set of experimental results for analysis. In many POGIL-PCL experiments, the first pass through the data-think cycle may focus on qualitative explorations of the chemical system, while further cycles develop quantitative data. The combination of qualitative exploration and quantitative data allows students to examine and apply mathematical models of chemical systems to both achieve a better understanding of the chemical phenomena and to motivate further questions and experiments.

This application of models typically happens in the "thinking about the data" (TATD) portion of the data-think cycle. A series of questions guides students towards development and application of the appropriate models. Students need to use the entire set of data gathered by the class to answer the questions. These questions should be answered collaboratively during the lab period with the intent of leading into another data-think cycle or providing the background needed to address post-experiment questions.

A POGIL-PCL experiment proceeds through several data-think cycles, each of which provides an increasing depth of understanding. Post-experiment questions after the last data-think cycle ask students to apply more complex models, consider related systems and phenomena, discuss improvements on the experiment, or otherwise apply what they have learned through doing the experiment and analyzing the data. Instructors have used these questions to motivate material that could be addressed in a formal lab report or as standalone questions on homework assignments.

An essential part of the POGIL-PCL process is instructor facilitation of student collaboration. The prediction/correction cycles are done collaboratively by the students, and instructor intervention is needed to promote classroom sharing verbally or on blackboards. Data pooling may be organized by the students or the instructor, but the instructor often has to initiate the process. Finally, when presenting predictions or conclusions, students may need prompting to include justifications supported by the entire class data, not just their own, for their claims.

Intended Effect of POGIL-PCL on Student Learning Outcomes

The POGIL method places a focus on both content and process: what should students learn, how do they best go about learning that content, and how can they apply both their content knowledge and process skills in future work. The general goals of the POGIL-PCL project and the specific POGIL-PCL experiment structure are consistent with this focus. Students explore a physical chemistry content area in each POGIL-PCL experiment, obtain data using standard methods, and develop and apply appropriate models to that data. In doing so, they develop process skills (teamwork, communication, management, problem solving, and others) that are necessary for being successful scientists. As physical chemistry is a course that provides a bridge between students' undergraduate work and their work in graduate school or industry, the use of POGIL-PCL experiments to develop these process skills occurs at a particularly opportune moment in their education. POGIL-PCL therefore provides key structures for students of the current generation:

- An approach to laboratory experiments that has the student be a partner in their learning, not just following instructions provided to them;
- A focus on process skills that develop independent thinking, strong communication skills, and the ability to work in a team; skills that are valued by graduate schools and employers;
- A model of how to combine learning content knowledge and developing process skills that will be particularly effective in the lifelong learning these students will need to do with the increasing expectation that they will not just change jobs regularly, but perhaps also career fields.

POGIL-PCL experiments may also stress experiment-specific process skills. The use of POGIL-PCL in computational chemistry described here develops computer and information technology skills while improving skills that are more generally applicable and valued across many disciplines.

Computational Chemistry in the Physical Chemistry Curriculum

Incorporating computational chemistry into the chemistry curriculum has been promoted by many, although as recently as 2011, Johnson and Engel claimed few programs included molecular modeling in the physical chemistry curriculum (*8*). A 1993 review by Casanova (*9*) of computer modeling in the chemistry curriculum suggests nearly all developments occurred after 1987. Karpen, *et al.*, described in 2004 an integrated wet/dry Physical Chemistry lab structure, with experimental and computational portions in alternating weeks (*10*). Dugas at University of Montreal (*11*), Sension at University of Michigan (*12*) and Ramos, *et al.*, at University of Porto (*13*) described full laboratory courses in computational chemistry methods. Strong arguments for the inclusion of computational chemistry include improvements of spatial visualization, training in near-ubiquitous research techniques, and investigation of systems too unstable or unsafe to study experimentally.

Student-accessible *ab initio* techniques have been available for many years; Wavefunction, Inc., published a workbook of organic chemistry problems in 1993, and Gaussian, Inc.'s *Exploring Chemistry with Electronic Structure Methods* (*14*) was also published that year. More recently, Hehre at Wavefunction, Inc published the comprehensive guide *A Guide to Molecular Mechanics and Quantum Chemical Calculations* (*15*). A number of molecular orbital (MO) experiments for use in the chemistry lab have been published (*16–18*). Among the prominent Physical Chemistry lab texts, Garland, Nibler and Shoemaker (*19*) include a few pages suggesting quantum chemistry extensions to some of the experiments, but state their focus is explicitly on laboratory measurement. Halpern and McBane (*20*) provide standalone quantum chemistry experiments that focus on calculation of thermodynamic quantities for a chemical reaction and molecular constants for HCl, which many students will find familiar from the classic HCl/DCl infrared spectrum experiment. Johnson and Engel wrote about integrating computational chemistry in the curriculum (*8*), and Engel's quantum text includes a full chapter on computational MO methods (*21*).

Molecular dynamics (MD) has been slower to penetrate the curriculum than MO studies. This is likely a combination of factors: MD is a newer field than MO methods, MD software is either prohibitively expensive or difficult to use, and MD results can be difficult to interpret. Early work on molecular modeling in the curriculum (*9*, *22*) typically focused on structural aspects, not dynamics, even though many of the strengths and caveats described in these articles apply to MD. The time required to perform MD simulations was a clear barrier, evident in the timing information presented in Reed's use of a two-dimensional hard-disk gas simulation in a physical chemistry lab exercise (*23*). Within a decade, these barriers started to decrease with, for example, reports on the use of MD in the physical chemistry lab to simulate systems with hundreds of molecules (*24*), and the development of user-friendly software packages, such as *Virtual Substance* or *Odyssey*, to facilitate student exposure to MD simulations (*25–27*). A number of uses of MD in physical chemistry lab exercises have been reported over the past 20 years. While exercises can focus on having students understand MD techniques (*28*, *29*), more published works emphasize using MD simulations to develop understanding of a specific system or chemical concept. Specific applications have included studies of intermolecular forces (*27*), conformational analyses (*30*, *31*) hydrogen bonding (*32*), and modeling of liquid and gas motions (*24*). These studies use a variety of software packages: homegrown, ones with a stronger educational focus—*Hyperchem* or *Odyssey*, for example—or research grade tools such as *Amber*.

A key trend for MO and MD calculations is that availability of research-grade software and in computational power even in desktop and laptop computers make a much wider range of computational studies accessible. Many interesting calculations hardly require more time than obtaining a UV-visible spectrum. As noted above, physical chemistry lab textbooks now include MO calculations at a high level of theory as readily expected options for wet experiments (*10*) or as standalone experiments, thereby establishing these methods as more standard techniques in the undergraduate chemistry curriculum. A more substantial example (by 2014 standards, anyway) of what is possible is the combined quantum mechanics/molecular mechanics/molecular dynamics physical chemistry experiment of Carlotto and Zebretto (*33*) exploring the solvent effects on the free energy surface of a dipeptide. These experiments show that a range from exploratory studies to near-research-level work is accessible at the undergraduate level.

Computational Chemistry Experiments in the POGIL-PCL Framework

We developed two computational chemistry experiments in the POGIL-PCL framework. These experiments address fundamental chemical concepts of chemical bonding, intermolecular forces, and thermodynamics in ways that provide a robust introduction to modern computational chemistry tools. The approach was to make these accessible to a variety of levels: one-semester overviews or more comprehensive multi-semester sequences (lecture and lab integrated in the same course, or lab as a separate course that may be taken in a completely different semester than the lecture). These experiments may be used in conjunction with POGIL physical chemistry activities such as those in the books by Spencer, Moog, and Farrell (*34*, *35*) or Shepherd and Grushow (*36*).

The design of these experiments acknowledges that many physical chemistry lab instructors have had little or no exposure to computational chemistry methods in their education and research, mirroring the experience of one of the authors (RMW) whose first time ever using a bomb calorimeter was when first he had to teach the bomb calorimetry experiment. We therefore developed experiments that can be implemented successfully by physical chemistry lab instructors who have little experience with computational chemistry. We further wrote the labs sufficiently general so that instructors could use whatever software they wished, while providing in the instructor's handbook more details about using common freely available software so as to provide a more turnkey approach for those instructors who would only use computational chemistry in the context of these labs.

The next section describes each experiment, providing a general overview of the learning objectives and methods used, as well as sample results obtained by students. We then show how these experiments adhere to the POGIL-PCL structure. Finally, we discuss the initial implementation of these experiments, by ourselves and others. Based on that implementation, we note some important lessons learned from using the POGIL-PCL structure to bring computational chemistry into the physical chemistry laboratory course.

Experiments

What Makes an Electron a Valence Electron?

The motivation for this experiment arose from frustration with students' inability to interpret the standard molecular orbital diagram beyond the stock questions about bond order and bond length (see Figure 2). Typically, students were able to reproduce the entire diagram (including obscure labels) without recognizing that the right and left sides represented the atomic orbital energies of separated atoms while the center levels represented molecular orbital energies of the molecule.

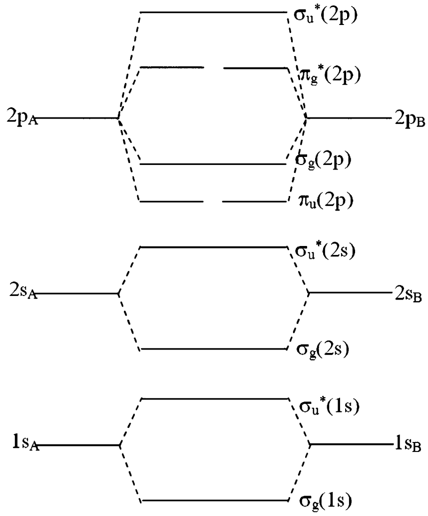

Figure 2. Molecular orbital diagram for second-row homonuclear diatomics.

In performing the experiment, the objectives were as follows.

- Content objectives

  1. Recognize the orbital size, orbital energy, and interaction differences between core and valence electrons
  2. Create quantitative orbital energy diagrams for atoms and molecules from calculational results
  3. Articulate the factors that control bond length (total energy and orbital energies)
  4. Explain periodic trends in molecular orbital energies across a series of diatomic molecules

- Process objectives

  1. Cooperatively organize data to form a coherent visual display
  2. Generate and analyze quantitative graphical depictions of data (in ways other than x-y plots)

While the experiment was developed using Gaussian03 for Windows (*37*) (G03W) and the associated graphical user interface GaussView (*38*), it has been

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successfully performed using Spartan (*39*) and WebMO (*40*). The computational requirements are low, with instructions suggesting Hartree-Fock level calculations with the standard basis set 6-31G(d). The most intensive assigned calculation is the optimization of F_2 (a job which can be completed in less than 1 CPU minute on the WebMO demoserver or with Gaussian G03W on a PC laptop with an Intel Core™2 Duo CPU T9400 @ 2.53 GHz).

The initial learning cycle begins during the prelab with students recalling the definition of a valence electron from general chemistry. In the first experiment, students calculate the total energy and atomic orbital energies for the first and second row atoms. The information is shared by the entire class so that students perform a small number of calculations, but are able to compare the trends for all ten elements. At the end of this experiment, the students revise their description of a valence orbital. An Excel template provides a structure for recording and displaying quantitative relationships of the atomic orbital energy levels; without this prompt, students tend not to organize the information systematically, even when verbally cued to do so.

In the second experiment, the connections between atomic orbital energies and molecular orbital energies are made using the Li_2 molecule. Students calculate the Li_2 total energy and orbital energies at interatomic distances from 0.5 to 50 angstroms. The data are shared and a potential energy diagram is constructed. Students are prompted to work cooperatively to choose a method to find the optimum bond length from their calculated points and perform additional calculations if they deem it necessary. The data near their chosen minimum are used to determine Morse potential parameters, and the students evaluate the fit of the Morse potential function to their data. Finally, students compare the effect of interatomic distance on valence and core orbitals, using this information to continue revising their valence electron definition.

An issue with fitting the Li_2 electronic energy as a function of the interatomic distance is that the Hartree-Fock wavefunction dissociates incorrectly to a singlet state rather than the triplet of two separated Li atoms, making the bond dissociation energy incorrect (*41*). The force constant, however, is unaffected. This issue is discussed (and corrected) in the postlab questions.

In the last experiment, students calculate the MO energies for all the 1st and 2nd row homonuclear diatomics, creating a master table and diagram from an Excel template. Individual students also use the data from Experiment 1 to create quantitative MO diagrams for one or two diatomics from another template. An example result is shown in Figure 3. While most electronic structure software will produce a diagram showing the ordering of the orbitals, they will not take data from atoms and diatomics and demonstrate the energy splitting from atoms to molecules as is done on the template. In addition, using the templates requires the students to examine the AO origins of each MO and recognize which sets of MOs are degenerate and which arise from the same set of AOs (for example, the 2pσ and 2pπ). The experiment ends with groups finalizing their descriptions of valence orbitals and core orbitals. Post-experiment questions encourage predictions about heteronuclear diatomics and extensions to the third period, with the option to perform these calculations.

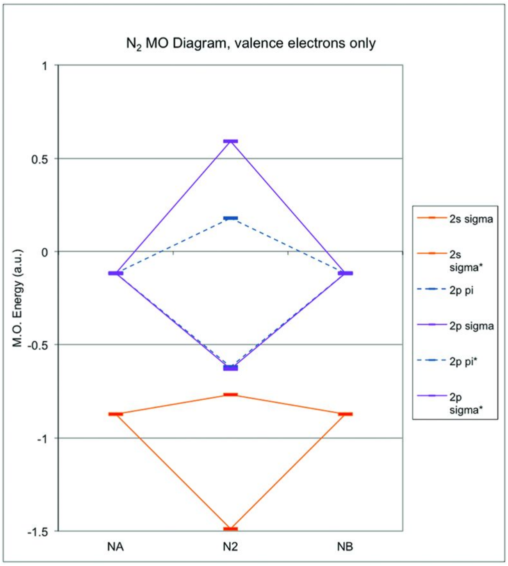

Figure 3. The 6-31G(d) molecular orbital diagram for N_2 created from an Excel line graph.

What Factors Govern the Escapability of a Molecule from a Liquid?

Students often learn in general chemistry courses that the boiling points of non-polar molecules have a direct relation to the magnitude of the short-range attractive forces known as London or dispersion or instantaneous dipole-induced dipole forces (and which we refer to here as van der Waals forces). The magnitude is then described to be qualitatively related to molecular volume, the points of contact that the molecule can make with other molecules, and/or the polarizability of the molecule's electron cloud.

This experiment builds a connection between that qualitative discussion of physical properties and intermolecular forces and quantitative molecular modeling, with an additional focus on providing an introduction to molecular dynamics simulations and force fields. Students generate both gas and liquid phase energy decompositions from molecular dynamics trajectories for pentane isomers and use that information to calculate enthalpies of vaporization. Through more detailed analysis, they demonstrate a direct relationship between boiling point, enthalpy of vaporization, and van der Waals energies while also showing that other intermolecular interactions are not correlated with boiling point for this series of non-polar molecules.

- Content objectives

    1. Describe relationship between molecular shape, van der Waals energy, and enthalpy of vaporization
    2. Differentiate between intermolecular and intramolecular interactions
    3. Understand the use of MD simulations in predicting macroscopic properties

- Process objectives

    1. Perform molecular dynamics simulations and visualize trajectories
    2. Perform energy decomposition and analyze contributions to total energies

The protocol for this experiment has been tested with students using the Tinker (*42*) molecular modeling package using the OPLS-AA force field (*43*). We have also tested the protocol with the NAMD molecular dynamics package (*44*) and the CHARMM General Force Field (CGenFF) (*45*). (NAMD was developed by the Theoretical and Computational Biophysics Group in the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign.) Both packages provide intramolecular and intermolecular energy decompositions, facilities for constant temperature and constant temperature/constant pressure dynamics, and compatibility with visualization software such as VMD (*46*). The NAMD/VMD tandem further provides the capability of monitoring the molecular dynamics as they are run. Any molecular dynamics package with similar capabilities can be used in this experiment.

The computational requirements for this experiment are not substantial and laptop or desktop systems can be used. For example, a single 10 ps trajectory in the 42 pentane molecule box we use typically requires less than five minutes on a MacBook Air with a 1.7 GHz Intel Core i7 processor. More than one trajectory can be run concurrently on systems with a multicore CPU. Students can readily obtain multiple constant temperature/constant volume and constant temperature/constant pressure trajectories in a single lab period. In the discussion below, we note several places in the procedure where the instructor may choose to provide initial coordinates for the molecular dynamics calculations or scripts for energy analysis to the students. This information is available from one of the authors (RMW) for using Tinker in this experiment.

This experiment focuses on the three pentane isomers (pentane, isopentane, neopentane; or pentane, 2-methylbutane, 2,2-dimethylpropane). The pentane isomers have substantially different shapes/volumes while controlling for functional groups, molecular formula, and molecular weight.

In the first experiment, the class assigns a single isomer for each group to study, with at least one group performing calculations on each isomer. Students are provided with coordinate files for a single molecule and a box of 42 molecules placed randomly in a volume corresponding to the density of pentane at 273K. Students use the selected software package and force field to minimize the energy of the box of molecules in periodic boundary conditions and observe the regular structure that emerges, particularly for the neopentane isomer.

Beginning with the minimized box of molecules, students run constant temperature molecular dynamics (NVT ensemble) for 10 ps at 273K, a temperature chosen because all three isomers show behavior corresponding to the liquid phase. This time span is sufficient for equilibration at the given temperature to take place as monitored by the total system energy and provide a sufficient time after equilibration for equilibrium energy averages to be calculated. At least five trajectories are obtained by each student group for their chosen isomer. Students thereby see that many independent trajectories are used to obtain equilibrium quantities from molecular dynamics.

Students run similar dynamics for a single isolated molecule of their chosen isomer. These trajectories are used to simulate the dynamics of the isomer in the gas phase at 273K.

While all the trajectories are being obtained, students are guided to visualize sample trajectories for both the gas phase and liquid phase systems. Students are guided to describe the trajectories, focusing on the characteristics that show whether a system is in the gas, liquid or solid phase.

When all trajectories are complete, students extract energy information from the program output. Besides the total energy, students examine the decomposition into potential and kinetic energy, and further decompose the potential energy into intramolecular energies (vibration, bend, and torsion) and (primarily) intermolecular energies (van der Waals, charge-charge). (van der Waals and charge-charge energies also have an intermolecular component due to non-bonded intramolecular interactions, but this component is not significant in this series of non-polar molecules. Interesting systems for students to explore further includes molecules which may have significant non-bonded intramolecular interactions in the gas phase, such as internal hydrogen bonding, that then become intermolecular interactions in the liquid phase.) Students calculate averages for each energy for each trajectory from an equilibrated region of the trajectory. In this calculation, students are guided to select the time step at which to begin the averaging rather than being told which time step to use.

For each isomer, students use the total energy or potential energy to calculate the cohesive energy of the system, defined as the difference between the energy of the 42 molecule box and the energy of 42 isolated molecules. The enthalpy of vaporization is the magnitude of the cohesive energy plus RT, a term arising from the conversion of energy to enthalpy (*43*). Students also decompose the cohesive energy into van der Waals and charge-charge energies and examine the relative magnitude of each.

Students pool their data to calculate average enthalpies of vaporization and average van der Waals and charge-charge energies for each isomer. Sample data from a physical chemistry class in Fall 2013 (7 students, 3 groups, each group performed calculations on two isomers) is shown in Table 1.

Table 1. Typical results for ΔH_{vap} for pentane isomers from molecular dynamics

Molecule	*Neopentane*	*Isopentane*	*Pentane*
ΔH_{vap} (calculated) (kJ/mol)	22.05	23.23	26.49
ΔH_{vap} (experimental (*47*)) (kJ/mol)[a]	22.39	25.22	26.75
van der Waals Energy (calculated) (kJ/mol)	-13.175	-13.705	-13.96
Charge-Charge Energy (calculated) (kJ/mol)	-0.00963	0.003675	-0.1031

[a] Experimental data obtained from the NIST Chemistry WebBook, http://webbook.nist.gov/chemistry/.

Students typically draw several conclusions from their data:

- The range of values for the enthalpy of vaporization and the van der Waals and charge-charge energies in the individual trajectories is quite large, but the average values for each isomer lead to a clear, identifiable (and perhaps expected) trend.
- The comparison to experimental data establishes the general validity of the method, with the computed ΔH_{vap} values differing from the experimental values by only a few kJ/mol.
- The intermolecular charge-charge interactions are insignificant with the average for each isomer being very close to zero and there being no clear trend in the isomers.
- The intermolecular van der Waals energies are both substantially larger than the charge-charge energies and show a trend that correlates with the ΔH_{vap} values.

Students can then connect these computational results back to their initial discussion of intermolecular forces and molecular shape. Their thinking about molecular shape is further enhanced by the visualization work they do during this experiment.

The second experiment is motivated by wanting students to make a connection between the equilibrium molecular dynamics from the first experiment and the dynamical process of vaporization or condensation. To that end, students run constant pressure/constant temperature molecular dynamics (NPT ensemble) on neopentane at 400K and 1 bar for 100 ps using the last step of a 273K molecular dynamics run as their initial conditions.

At this temperature and pressure, the system achieves a much lower density over the 100 ps indicative of a phase transition taking place. (However, 100 ps of dynamics is not sufficient for the molecules to achieve intermolecular distances that are typical of gas phase molecules at this pressure and temperature.) The final system provides starting conditions that allow students to explore potential condensation behavior as the temperature is lowered. The class agrees upon the temperatures to be studied (all at 1 bar pressure) and assign temperatures to each group. Each student group runs 100 ps of dynamics starting with the 400K configuration at the specified temperature. Through examination of the density over the last 10 ps of dynamics, students can decide whether the system has condensed to the liquid phase or remains in the gas phase.

Typical results are shown in Figure 4. While the vaporization temperature is significantly different from the experimental values, students see that the sudden change in density indicative of a phase transition is reproduced through these simulations. Students use energy decomposition to show that the intramolecular van der Waals energy is the only energy that changes significantly during the vaporization (condensation) process. Finally, students use visualization to develop mental models of the vaporization process. In particular, they can see that even as the density drops sharply, there are still some clusters of molecules, indicating that vaporization does not necessarily happen molecule by molecule at first, but instead through the development of "holes" in the liquid system that grow.

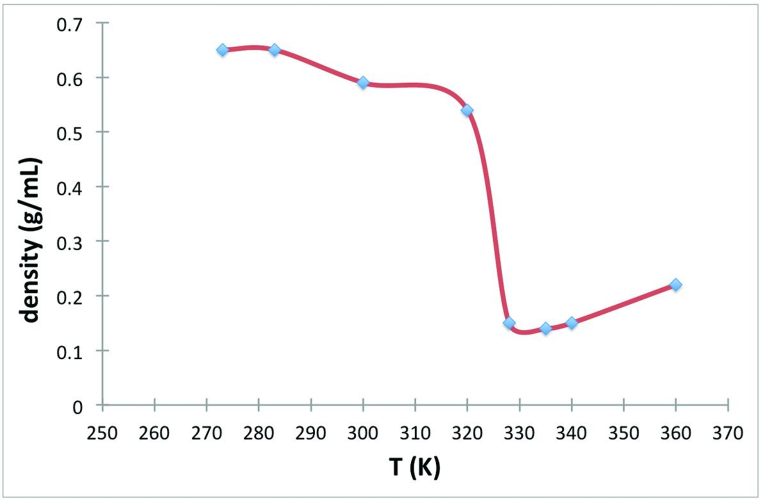

Figure 4. Neopentane density as a function of temperature as calculated from molecular dynamics

Discussion

POGIL-PCL and Computational Chemistry Experiments

We have described here two computational chemistry experiments that implement the goals of the POGIL-PCL project, adhering to an inquiry-based structure that enhances student content knowledge and process skills.

Each experiment consists of at least two "data-think" cycles that have students explore increasingly complex elements of the system with each pass through computational work and data analysis. In the valence electron experiment, the calculation of electronic energy levels for atoms in the first cycle allows students to explore a concept that is familiar to them from previous chemistry classes, but now in the context of computational quantum chemistry. The two successive cycles operate at a higher conceptual level, introducing the concept of a potential energy curve in the second cycle and then applying the knowledge to the entire set of first and second row homonuclear diatomic molecules in the third cycle.

The molecular dynamics experiment begins with a similar exploratory cycle that introduces students to the concepts of molecular dynamics, force fields, and trajectory visualization, all in the context of the molecular dynamics of pentane isomers. In this cycle, students also explore the decomposition of a system's energy into a variety of components, none of which are measurable directly through experiment. Students use gas and liquid-phase trajectories to calculate enthalpies of vaporization in this cycle, which then leads to the more complex topic of simulating vaporization/condensation in the second cycle.

As in all POGIL-PCL experiments, prediction is a key component of the experimental structures. Prior to doing the experiment, students are expected to use their existing knowledge to make *reasonable* (not necessarily *correct*) predictions of chemical phenomena that will be tested against the computational results. For example, in the valence electron experiment, students are asked to predict the characteristics that distinguish valence electrons from core electrons. And in the molecular dynamics experiment, students predict whether *n*-pentane has a higher, lower, or the same boiling point as neopentane. In all such predictions, students are asked to explain their predictions. In doing so, they readily make connections to concepts they have explored, typically on a qualitative level, in previous chemistry classes.

After students perform the computational experiments in each cycle, "Thinking About the Data" guided inquiry questions help them perform the necessary data analysis, interpret the results, and prepare them to transition to the higher complexity of the next data-think cycle. These questions often start by directing the students to pool their results and answer questions based on the collective set of data. Students are typically asked to evaluate their prior predictions in the context of their data, identify trends in their results, and begin to address the conceptual question that is the title of the experiment. In the molecular dynamics experiment, students rationalize the computed enthalpy of vaporization based on the decomposition of the intramolecular and intermolecular energies that the calculations give access to. In the valence electron experiment, students use both the computed energies and orbital visualization to improve upon their original description of what identifies an electron as a valence electron.

It is a goal of POGIL-PCL experiments not to make the experimental protocol overly prescriptive. These computational chemistry experiments adhere to that goal by providing general directions about how to use the software and the computational parameters, but not always specific instructions about which calculations to do. In particular, it is expected that the class will evaluate the range of calculations that must be performed and divide the work so that not every student does every calculation and pooling of the class results is required to develop a full understanding of the chemical system. For example, in the molecular dynamics study of vaporization/condensation, each group of students performs NPT-ensemble calculations at several different temperatures. When all the class results are incorporated into one data set, students can see the patterns that indicate which phase (gas or liquid) the system is in and can also decide, as a class, what further calculations are necessary to obtain a fuller description of the phase change behavior.

These computational experiments have been developed to give reliable and reproducible results, but results that students do not know in advance so that they do not see the goal of the experiment as reproducing existing calculations. In the molecular dynamics calculation of enthalpies of vaporization, for example, students run many short trajectories to obtain a reliable average value. In doing so, they mirror the technique of researchers who use molecular dynamics calculations, but at a scale appropriate for the physical chemistry lab class.

It is in fact a general theme of the POGIL-PCL computational chemistry experiments that student calculations are not at the highest level of theory or computational method available. The general protocol is chosen to give reliable results that illustrate the key concepts in a reasonable amount of time. We attempt to find a balance in the student effort between conceptual development and high-precision calculations. Therefore, the valence electron experiment focuses on small atoms and molecules using the 6-31G(d) basis set and the Hartree-Fock model. The molecular dynamics experiments rely on short runs and simple force fields. In both cases, the methods can be understood by physical chemistry students without being so simplified as to give unreasonable results.

Each experiment ends with the set of post-experiment questions that guide students to apply their understanding developed during the experimental work. In the valence electron experiment, students can explore different systems, such as heteronuclear diatomics, vibrational frequencies in diatomic molecules, or higher levels of molecular orbital theory beyond Hartree-Fock. For the molecular dynamics experiment, students can investigate the energy decomposition more thoroughly as well as perform calculations on different systems, such as ones where hydrogen bonding plays a key role. Such work can lead students to develop research projects or independent studies that can extend the learning beyond the physical chemistry laboratory class.

Lessons Learned and Unexpected Outcomes

In developing two POGIL computational chemistry lab experiments while involved in the development stages of other experiments, we have learned a few pitfalls arising purely from having students use computers. We also determined that the visualization of orbitals, energy levels, and liquid motions imparted visceral "ah ha" moments to a number of students. Lastly, we learned that students, even with guidance, are not likely to spontaneously create unusual plots and graphs. Providing templates reduces frustration levels and allows the students to progress to a critical examination of the data.

Lab experiments requiring that students use an instrument they have never before used are de rigueur in the physical chemistry lab. Showing a block diagram, giving the basics of operation, and handing the students a manual or instruction sheet are the normal steps to introducing a new instrument. Using a new piece of computational software on the surface seems no different (and, in fact, seems more safe), but we have observed an additional layer of anxiety for the students.

In the initial testing of these two experiments, the authors discovered that computational experiments have the complexities of the experimental steps intertwined with the complexity of using software on a computer. Students (and faculty at workshops) are not always clear on what actions were computational procedures and what steps were merely requirements of an operating system. For example, in the pentane MD experiment, operations such as changing directories in a terminal window and making a command line entry were not differentiated by students from the computational procedure steps such as choosing whether to minimize or run dynamics. This category error became obvious in their lab reports. We have attempted to address this specific issue by providing simpler interfaces that permit focus on the parameters of the computational experiment and deemphasizing the underlying tools.

Output from a computational program comes in the form of reams of numerical data, often sparsely commented, and an array of possible graphical displays and visualizations. The nitrogen diatomic molecule in the 6-31G(d) basis set has 30 molecular orbitals, each of which has an energy and a visual shape; the molecule has an additional total energy which is not obviously related to the orbital energies. A collection of pentane molecules, after 10,000 steps of NVT dynamics, has 10-1000 sets (depending on how often the data are saved) of total, potential, kinetic, van der Waals, electrostatic, and bonded energies, and other quantities such as temperature and pressure. Each set also has a collection of atomic coordinates which can be viewed as a snapshot of the pentane liquid or gas. This is a lot more data than an absorbance measurement, which typically involves a wavelength, an absorbance, and a concentration. Students need training in scanning output for results, at times in multiple places on the screen or in different files that were generated.

The molecular orbital diagram in Figure 3 was created using the line graph feature in Excel. The y-axis is orbital energy, but the x-axis is a category axis, with the orbitals for the N_A atom on the left, those for the N_B atom on the right, and the N_2 molecular orbitals in the center. This is not a conventional use of Excel. Yet, while students in Physical Chemistry have typically seen Figure 2 in several prior classes, sketching a diagram similar to Figure 2 or Figure 3 with a y-axis to scale does not occur spontaneously or even with heavy prompting. Students are also unlikely to create a more complicated diagram such as the periodic trends in orbital energies. In the end, the amount of verbal and written prompting to get students to develop their own visualizations was insurmountable, and templates were developed. This eased frustration and allowed students to enter data quickly. It also allowed students to spend more time contemplating trends in the results. Simpler representations, such as Li_2 energy as a function of bond length or energy vs. time in an MD calculation, did not require templates, although extracting energy data from the MD data files can be simplified by scripts provided to the students.

Using computational chemistry methods to generate molecular orbitals, orbital energy diagrams, models of moving liquids, and simulation of vaporization has led to numerous "ah ha" moments among the students. The MO diagram of

Figure 3, which is constructed in Excel from the student's own data, has led to these. Similarly, the decomposition of energy into intermolecular and bonding pieces gives the students the data necessary to understand the role of dispersion forces in vaporization. Once students become comfortable with the software and start experiencing the "ah ha" moments, they begin to see the value of computational studies, in which many ideas can be quickly tested. For example, when students pool their data to develop the neopentane density plot as shown in Figure 4, they realize that they have the tools to quickly fill in the gaps and obtain better data about the change in density at the phase transition. Through the use of post-experiment questions and the students' own ingenuity, the POGIL-PCL computational chemistry experiments allow students to see the value of these methods in understanding chemical phenomena and build their confidence in their use.

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Chapter 7

Undergraduate Research as Pedagogy: Promoting and Sustaining a Culture of Undergraduate Research among Chemistry Majors

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In contrast to the growing body of evidence suggesting students engaged in undergraduate research (UR) achieve better outcomes, we have observed declining interest among our students in UR opportunities, despite increases in the number of matriculating majors. A preliminary survey indicated that the decline in interest was anchored in two important perceptions held by the students: UR is time-consuming and will detract from their academic success and a lack of prestige associated with UR. Interestingly, students overwhelming indicated that the experience would be valuable to their future goals. We addressed these concerns by initiating a comprehensive study of students and faculty, and report herein on how results were used to develop a roadmap for a sustainable and robust UR program. From this analysis, we conclude that a successful program requires intentional recruitment mindful of millennial characteristics and a reward structure that supports faculty involvement. This approach will prove useful to faculty and administrators seeking value-added interventions to educating millennial students.

Background

Almost two decades ago, the landmark Boyer Commission report (*1*) urged universities to reinvent undergraduate education in order to equip and prepare U.S. students to excel in a complex 21st century global labor force (*2*). Yet, in the science, technology, engineering, and mathematics (STEM) disciplines, the number of highly qualified graduates has not kept pace with workforce demand, forcing the U.S. to seek substantial expertise from other countries. In response, the President's Council on Science and Technology issued a national call to *Engage to Excel* (*3*) citing the need for one million more STEM graduates by 2022. The report provided specific strategies for improving undergraduate STEM education, including empirically validated teaching practices, discovery-based research courses, rigorous teacher preparation, and faculty professional development, partnerships to diversify pathways to STEM careers, and strategic leadership for transformative, sustainable change.

In 2005, the Council of Undergraduate Research and the National Conference on Undergraduate Research issued a joint statement acknowledging undergraduate research as "the pedagogy for the 21st century" (*4*). Mounting evidence (*5*) suggests that effective mentoring pedagogies between a faculty mentor and an undergraduate student build a vital bridge between the traditional classroom and the preparation experience that graduate schools, corporations, businesses, government, and industry demand. Lopatto (*6*), for example, found that students participating in summer undergraduate research experiences learn tolerance, experience increased independence and self-confidence, and become ready for more demanding research – advantageous dispositions in any career path. When compared to alumni with no undergraduate research experience, Bauer and Bennett (*7*) found that graduates with research experience reported greater enhancement of important cognitive and personal skills as well as higher satisfaction with their undergraduate education. These alumni were also more likely to pursue graduate degrees, consistent with other studies (*8*, *9*) that showed a higher likelihood of graduates attending professional schools. In addition, Mabrouk's (*10*) assessment of chemistry students' experiences at two American Chemical Society national conferences revealed that student presenters perceived conference participation as an important element of the research experience and a vital factor in their enculturation into the scientific community. Further, recent reports (*11*, *12*) indicate that employers are relatively content with students' technical readiness for employment but prefer experience over academic record. In fact, undergraduate research (UR) as a specific pedagogy promotes the college learning outcomes psychologists suggest require special developmental attention at the undergraduate level (*13*) to help the millennial student develop complex capacities critical to thrive in a highly demanding global context (*14*, *15*) – the ability to work effectively in teams of diverse people, communicate well, make decisions, think critically, find and evaluate options, and draw sound logical conclusions.

This issue is not new, however. Focus and attention on the dire need to improve STEM undergraduate education to foster learning experiences steeped in inquiry that address the millennial learner has been long advocated by a number of national agencies and organizations including Project Kaleidoscope (*16*), the Council on Undergraduate Research (*17*), the National Science Foundation (*18*), and the American Chemical Society (*19*). Consequently, UR as a high impact pedagogy of engagement (*20*) has gained substantial momentum, with a number of studies in STEM disciplines demonstrating the value-adding dimensions of the research experience – namely, synergistic enhancement of teaching and research (*21*), psychosocial and skills-based benefits to the mentor, undergraduate, graduate schools and the world of work (*22*), campus-wide intellectual vibrancy (*23*), diverse and inclusive participation (*24*), enhanced faculty engagement (*25*), and bridging theory and practice (*26*).

Undergraduate Research as Reform Pedagogy

The quest to lessen the mismatch between science and science education has prompted educators to seek pedagogies where students appreciate how evidence is used to construct scientific knowledge. According to the Association of American Colleges & Universities report *College Learning for the New Global Century* (*27*), "The key to educational excellence lies not in the memorization of vast amounts of information but rather in fostering habits of mind that enable students to continue their learning, engage new questions, and reach informed judgment." However, during their developmental years and pervasive throughout college, students are generally told what chemistry is and asked to remember chemistry facts (*28*). Evidence on how people learn suggests that student-centered, student-situated participation in shared endeavors with others in "a process of transformation of participation" (*29*) fosters integration of new and prior knowledge such that learning is "continually constructed and reconstructed by the individual" (*30*). Therefore, UR as an apprenticeship-model advances social practice and constructivist learning to elevate cognitive growth and professional identity while bolstering the millennial's ability to think critically, find and evaluate options, and draw sound logical conclusions.

The Millennial Learner and Engagement Pedagogies

In raising the question of what educators mean by engaged learning, Bowen (*31*) proposed four hierarchical categories (Figure 1), which are foundational to UR as a pedagogy of engagement. The first category, student engagement with the learning process, places the engaged learner as an active participant in the co-creation of knowledge rather than a passive recipient of expert knowledge. In the chemical sciences and related disciplines, self-directed undergraduate researchers engage in what Lopatto (*32*) describes as "self-authorship" and "probing commitment" in seeking answers or truths to fundamental questions. Student engagement with the object of study, the second category, focuses on learning situations where students have direct experiences such as laboratory research, internships, practicums, fieldwork, or other applied learning – activities natural to the chemical sciences. The third category is student engagement with the contexts of the subject of study. At one sublevel, this category reflects the importance of studying a topic or issue from multidisciplinary perspectives.

At another level, this category reflects ethical dimensions of what students are studying. Research by undergraduates ranges from unidisciplinary experiences to a continuum of integrative, multidisciplinary offerings with a broad scope of ethical implications targeting capacious, examples of global challenges – water resources, climate change, world health, and energy use. The fourth category, student engagement with the human condition (especially its social, cultural and civic dimensions), cannot be accomplished through traditional, classroom-based approaches. Learning at this level requires that students leave the relative comfort and security of the classroom to experience directly the socio-cultural contexts in which what they are studying occurs. This type of engaged learning aligns closely with community-based chemistry research.

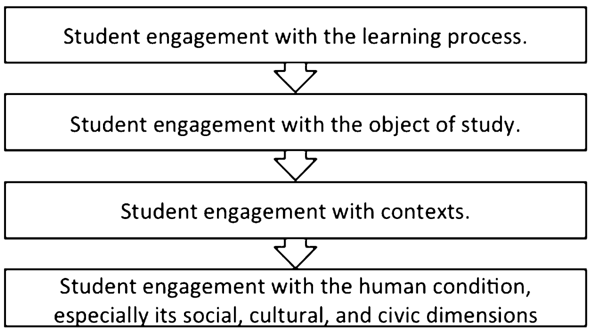

Figure 1. Bowen's Categories of Engaged Learning

The millennial student has been described as focused on achievement over personal development, pressured to succeed, and socialized to respond to direction. The millennial student experiences a tension between an internal desire to achieve and external pressures to conform. Engagement and learning through research as described by Bowen's conceptual framework embraces the communal, inquiry-based nature of chemistry research. Tacitly, effectively-mentored UR encourages, develops, cultivates, and reaffirms important civic-minded, self-directed, risk-taking dispositions critical to success while combating competitive, conformist traits observed among millennial students. Bowen's approach to UR conflicts with the traditional structure of research-intensive universities, which requires students to work independently and seek their own mentors.

Establishing a Culture of Undergraduate Research

Student Roadmap for Undergraduate Research

Georgia College, founded in 1889 received a new mission in 1996 as Georgia's Public Liberal Arts University (*33*). Most (>90%) students are residents of Georgia and of those, the majority enter Georgia College with SAT scores significantly higher than the national average and receive a merit-based tuition scholarship from the state. Eight tenure-track faculty meet the teaching, research, and service requirements of the Chemistry Program in addition to serving a large external demand for chemistry courses to non-chemistry majors. Roughly 50% of students in the chemistry program have declared a pre-medical, pre-pharmacy, or pre-dental concentration. Over the past 10 years, the number of declared chemistry majors has increased by 53%, while the number of freshman declaring the program has remained relatively constant. Since 2008, the program has demonstrated strong freshman to sophomore retention (~70-80%); however, enrollment declines significantly between the sophomore and junior years (~50%). Many factors contribute to this loss of students but the majority either change their major or transfer to another institution.

In response to surging enrollments and institutional pressure to increase student retention, which are ongoing issues in higher education, faculty in the chemistry program have been engaged in important curricular reforms that ensure students are continuously challenged academically and engaged in the practice of chemistry. Most recently, we revised our program goals to focus on learner-centered outcomes and highlight the experiential learning that has become a cornerstone of our program. In their entirety, the program's new learning goals reflect the many components involved in developing the skills, abilities, and dispositions necessary for research in the chemical sciences. However, five of the goals specifically address the activity of UR, which have been paraphrased below:

1. *Students will design experiments*
2. *Students will transform data into evidence*
3. *Students will derive a logical argument*
4. *Students will write and present scientific research in the chemical sciences*
5. *Students will demonstrate professional dispositions*

The revised program goals allow for high-impact pedagogies and innovations in teaching to be incorporated into the program in an effort to engage and support students in the practice of UR. This is evident in the curriculum, in student achievements, and through faculty assessment. The program offers a variety of activities that support student success through UR and provides a clear roadmap for a robust UR program (Figure 2).

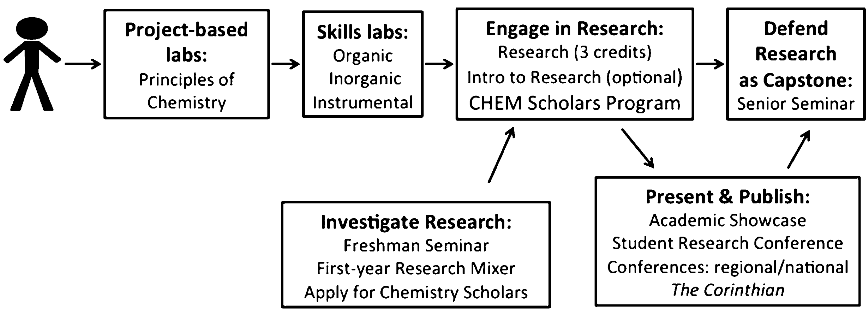

Figure 2. Student Roadmap for Undergraduate Research

Students in the chemistry program first engage with UR through the First-year Laboratory Sequence for Chemistry Majors (CHEM 1211L/1212L). Designed as project-based laboratory courses, activities facilitate use of appropriate knowledge, laboratory techniques, and data analysis to solve problems and prepare students for undergraduate research. Opportunities for oral scientific presentations, which develop essential communication skills and professional dispositions, are introduced to first-year students in the form of poster presentations that require students to analyze and present chemical data and literature. These introductions in the first-year are designed to serve as the gateway through which students encounter UR. Further, first-year course experiences establish expectations for students' continued participation in mentored research.

To further emphasize that undergraduate research is a component of our program philosophy, research experience is now a program degree requirement. All chemistry majors complete a minimum of three credit hours of supervised research (CHEM 4999) prior to graduation, although many students complete significantly more credit hours as they matriculate. Although this requirement provides invaluable faculty-student mentoring, it also presents a significant time commitment by faculty members. CHEM 4999 does not count as part of the required teaching load and is taught as an overload. As such, research opportunities are voluntarily offered by the faculty.

The chemistry capstone course (CHEM 4920) provides the clearest evidence of how revisions to the curriculum have led to students demonstrating gains in program goals. In this course, students prepare a research presentation and a portfolio comprised of evidence of their progress in meeting the program goals. Through gradual revisions of the course and the development of an evaluation rubric aligned with the program goals, we have observed student performance improve over time – presumably as a result of deliberate developmental offerings at all levels of the program – that provide students multiple opportunities to refine their skills in communicating scientific knowledge. For example, formal oral presentations are required in the sophomore and junior-level seminar courses.

Outside the curriculum, the program offers a variety of activities, all of which are transferable to other institutions and disciplines. In order to encourage early engagement in UR, all first-year chemistry majors attend a "Research Mixer" where they participate in a scavenger hunt that encourages conversations with upperclassmen in a scientific poster presentation format. Students engaged in research can share ideas through monthly "Journal Club" meetings whereby each month a different research group is responsible for leading a discussion about a chemistry journal article related to their research. Most notably, the Chemistry Scholars Program is an important highlight of our UR program. Each year, students selected from the freshman class receive funding and research mentorship from a faculty member in the department through a competitive application process. This scholarship provides support for the student to present at professional chemistry conferences or purchase supplies for research projects. Figure 3 depicts a freshman chemistry scholar as she learns laboratory techniques from her research mentor. The chemistry scholars also function as "departmental ambassadors" and as an advisory committee for the departmental chair. In spring semester of each year, the program hosts a "Research Showcase" where graduating seniors and chemistry scholars present their research to the faculty and their families in a full-day event celebrating the successes of chemistry majors. The prevalence of activities afforded our students has led to an increase in the number of students engaging in UR.

Figure 3. A first-year chemistry major practices laboratory techniques under the guidance of her faculty research mentor.

The success of our UR research program is evidenced by the myriad of student publications, presentations, and prestigious awards. For example, over a recent two-year period, UR conducted in the chemistry program has resulted in a total of 156 presentations – 51 local, 20 state, 38 regional, and 47 national/international. Furthermore, as a result of excellence in UR content material and presentation skills, eight of our chemistry students received national recognition from the American Chemical Society and five were awarded National Science Foundation (NSF) sponsored Research Experiences for Undergraduates (REU) grants. Furthermore, a student earned the distinct honor of a publication in *Inorganic Chemistry* (*34*) and another student was awarded a prestigious Mayo Clinic Summer Undergraduate Research Fellowship. Chemistry majors

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consistently represent a strong showing at our institution's annual student research conference, with an average of approximately 15 presentations annually.

The chemistry program's curriculum and activities provide a platform for significant achievements by students, which has led to a strong culture among students and faculty for integrating UR into all aspects of the student experience. Evidence of this culture is seen in student responses to the National Survey of Student Engagement (*35*) (NSSE), in which students in our program report higher levels of engagement in all five benchmark categories when compared to the university as a whole.

Student Challenges

Despite the significant accomplishments by students who engage in research experiences early in their major, we have seen a decline in interest in our Chemistry Scholars Program. The scholarship was popular with students when initially implemented in 2004 but the numbers of applications have gradually decreased since 2009 despite a relatively constant number of majors in the program (Table 1). This decline in interest is of concern because it indicates students are choosing to seek research experiences later in their degree process, leading to a decrease in the quality of research presentations in the senior capstone (CHEM 4920).

Table 1. Chemistry Scholar Applications: 2009 - 2013

Year	*No. Majors*	*CHEM Scholar Applications*
2009	104	16
2010	110	12
2011	104	20
2012	110	10
2013	102	8

In order to address this concern, we developed a modified version of the Undergraduate Research Student Self-Assessment (*36*) that investigates student attitudes about research. The survey was modified to garner student feedback specific to the Chemistry Scholars Program and administered to chemistry majors through 1-credit seminar courses offered each year. We received 73 responses, which corresponds to a 66% response rate. The majority of respondents were first year freshman (n=36) and of those, 58% indicated they did not apply for the Chemistry Scholars Program compared to 39% of the upperclassmen surveyed. This significant decrease is likely indicative of the role early involvement in research plays in student retention.

When asked to provide reasons for not applying to the Chemistry Scholars Program, students' responses were clustered into several categories. Most commonly, students indicated they are weary of committing time to research (29%), have difficulty meeting the application deadline (26%), feel they are undeserving of the scholarship (23%), are concerned about adding extra work (23%) or are not adequately informed of the opportunity (23%). Interestingly, very small percentages (10%) are not interested in the opportunity. These survey results mirror an initial study in which students indicated that research experiences would be valuable to their career but devoting time to research would detract from their academic success. In contrast to student concerns, we have evidence that students engaged in research develop skills important to the chemical profession. For example, 71% of students engaged in research reported that they have attended research conferences and just over half (57%) have presented their own research at a professional conference.

Our survey results demonstrate that while students understand UR is important, they do not value the experience enough to engage early in their tenure at college. The most significant decrease in applications for our early research program occurred in 2013, which coincided with a university-wide move to professional advising. While we do not suggest that professional advising is the sole cause of the decrease, it does highlight the importance of faculty mentoring opportunities for new students in order to communicate the significance of undergraduate research. Consistent, effective mentoring is specifically important for millennials because their focus on achievement over learning results in delaying faculty-mentored research until later in their degree. This lack of student-faculty interaction further perpetuates a lack of focus on learning for personal development. As an example, we have observed a decline in the number of students initiating conversations with faculty about research opportunities.

Strategies for Student Success

The chemistry program has implemented several initiatives to address these student challenges. In 2012, as articulation of how quality is defined, promoted, and assessed in the program, the faculty came together to write program goals. This undertaking involved mapping all courses and course outcomes to identify common program goals; identifying which goals were concrete, student-centered, and measurable; and ultimately developing five overarching program goals that reflect the knowledge, skills and dispositions we expect of students that successfully complete the chemistry program. The resulting goals now form the basis of student assessment in the capstone (CHEM 4920) experience. In addition to establishing student-centered program goals, the program includes a variety of structured activities designed to introduce students to UR as freshman, such as the Research Mixer described earlier. To further capitalize on the dispositions of millennials, the program also includes several opportunities to reward and celebrate students who demonstrate success in undergraduate research, which include an end of the year event where students can showcase their accomplishments to family members and other guests.

Above all, we have found that faculty-student mentoring is the best strategy for involving students in research early in their academic careers. The relationship pedagogy through mentoring in the early stages of a student's matriculation develops deeper awareness of signature skills and dispositions as a result of observation and explorations of inner intellect, self-efficacy, and metacognition (*37*). All of the interventions we have described require significant contributions from program faculty outside of their required course load. Identifying strategies for motivating this additional time will be important to sustaining an UR program.

Faculty Challenges

Although UR provides invaluable experiences for our majors, it also presents significant challenges to program faculty. As identified by our study, mentoring by faculty early in the undergraduate career is essential to student success in UR. Yet, this time-consuming key component is often voluntary and not included when determining faculty workloads. As mentioned previously, the program's three credit hour research requirement, CHEM 4999, is not included in the required faculty contact hour production. Thus, program faculty willing to engage in mentoring of undergraduate research students do so without teaching workload reductions. The time commitment to mentor undergraduate research students early in their undergraduate career is compounded with additional challenges: (1) first-year undergraduate students are not properly prepared or trained for UR; (2) training is conducted primarily by faculty as opposed to graduate students; and (3) once properly trained, students graduate resulting in a never ending cycle of training of new students. Such challenges, which are not limited to our program and often encountered by faculty across institutions, present limitations to a goal of engaging first-year students in faculty-mentored research.

Strategies for Faculty Success

In an environment where the resources to address workload issues are not available, we have implemented a faculty evaluation reward system designed to contribute to the sustainability of our UR program. Contributions to UR have become an expectation for program faculty and are rewarded through the annual faculty evaluation as well as tenure and promotion (T&P) policies. Our program benefits from a T&P system in which evaluation policies are established within the program and committee recommendations are reversed only in extenuating circumstances. Faculty evaluation criteria for teaching and scholarship drafted inclusively by program faculty reflect what we value as a group. In a peer-review, emphasis is given to excellence in UR mentoring, faculty-student publications, and curricular development, which includes UR and scholarship of teaching and learning (SoTL). Notably, our T&P policy places greater merit on faculty-student research than independent faculty research. This transferable evaluation structure not only rewards faculty for mentoring students in research, but also establishes expectations that all faculty engage in the practice, which adds to the sustainability of the UR program. Since faculty evaluation criteria are directly linked to our student-centered program goals, this sets an expectation for students to actively participate in UR. These strategies provide a roadmap for faculty, depicted in Figure 4, that has allowed us to create a sustainable UR program.

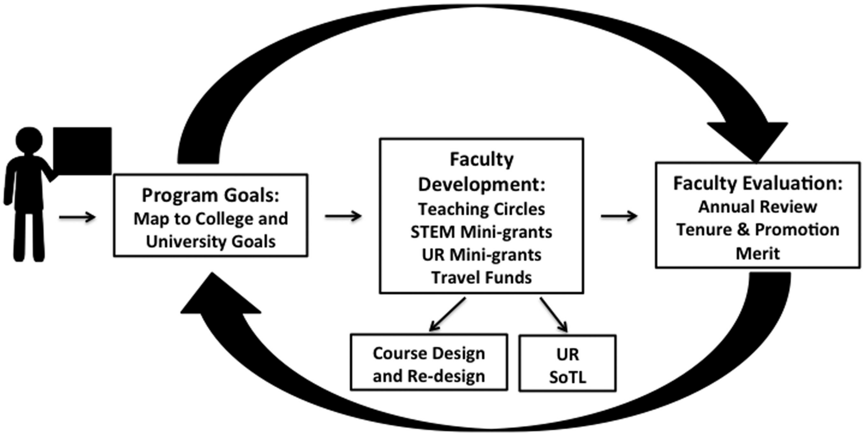

Figure 4. Roadmap for Sustaining UR and Rewarding Faculty

Sustaining a Culture of Undergraduate Research

Our implementation of this sustainability plan is in its infancy. We will continue gathering and analyzing data as we continue implementation in order to determine the efficacy of our strategy. To complement the student survey, we are in the process of developing a survey to identify faculty perceptions regarding our UR program and the associated workload. We are also interested in extending this study to include similar departments at different institutions.

Recognizing that undergraduate chemistry programs vary at different institutions, some of the challenges and strategies presented herein are generalizable to programs that serve millennial students. The primary lesson we have learned from this study is that program activities and curriculum need to be intentionally designed to address the experiences of the millennial student. In particular, integration of engagement pedagogies such as UR into the curriculum helps pave the way to their success. We also recognize that another strategy important to educating millennial students is intentional mechanisms for faculty mentoring early in their college experience. Specifically, faculty mentoring through UR capitalizes on what millennials want – active, socialized, collaborative, relevant, and connected learning experiences that are more creative. Further, we have found that the best way to sustain high levels of faculty involvement in mentored research is through a well-established reward structure. The nexus between seamlessly aligned program and learning goals, early access to mentored research, and UR as a value in faculty accountability has the potential to foster deep transformative outcomes for the millennial student.

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Chapter 8

An Integrated Approach for Development of Scientific Writing Skills in Undergraduate Organic Lab

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Scaffolding and peer review methods were combined on an online platform to develop scientific writing skills in an undergraduate organic chemistry lab. Collaboration was encouraged throughout the semester. First students anonymously critiqued lab report sections from their peers through the online platform. Later, small groups produced complete reports built up from the sections covered by peer review. Each student served a different role in the group, moving from a collaborative approach towards independent writing. The culmination of the semester was a complete report, produced independent of peer or instructor guidance. Implementation was accomplished through a series of rubrics, worksheets, and instructor feedback. Preliminary assessment of these curriculum changes indicates that student writing skills improved and that student feedback is mixed, but generally positive. The ultimate goal is the development of writing skills in lower-level chemistry labs in preparation for writing-intensive upper-level labs.

Introduction

Writing Skills and Critical Thinking

Critical thinking skills and the ability to write well are related. Writing, especially scientific writing, requires the ability to evaluate and interpret data,

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draw conclusions from these data, and communicate these conclusions in a concise and logical fashion (*1*). "When we make students struggle with their writing, we are making them struggle with thought itself" (*2*). "We believe writing is the tool of thinking" (*3*). The ability to write well is not valued solely by scientists as is evidenced by "Writing Across the Curriculum," a national initiative started some 40 years ago wherein faculty from disciplines outside of English incorporate writing instruction into their curricula (*4*). The importance of writing skills is certainly evident within undergraduate chemistry curricula (*5–7*).

For most students, sophomore organic chemistry laboratory is the first time in their academic career where they are exposed to scientific writing. While most have had English composition, there are differences between the two genres. Creative writing is characterized by imaginative or symbolic content, written in a subjective style. Accuracy and clarity are not central requirements. The content in scientific writing is factual, dictated by the content and purpose of the thesis, and accuracy is essential (*8*). Students must develop the skill of scientific writing not only to be successful in the organic laboratory but also in upper-division chemistry classes and other STEM courses which require formal reports. Developing this skill requires both time and practice.

Demographics for Organic Chemistry Laboratory

Organic chemistry at the University of Alabama at Birmingham (UAB) is a two semester course with corresponding laboratory courses which can be taken concurrently with lecture. The demographics for the Organic Chemistry I lab taught in Spring 2013, Fall 2013, and Spring 2014 are shown in Table 1. The majority of the students enrolled are sophomore-level biology students with career goals in medically-related fields. While 15-20% of the students enrolled in the laboratory are chemistry majors, there is also an honors laboratory course offered that some chemistry and engineering majors enroll in.

Motivation for Change

Laboratory sections can accommodate up to 30 students and students work in groups of three. Historically, students submitted a total of eight group lab reports. These were formal reports which required introduction, experimental, results, discussion, and conclusion sections. Students divided the sections amongst themselves and wrote the sections individually. When assembled into one document, the sections did not fit together well. Students often also had difficulty writing adequate conclusions. A clear lack of editing resulted in use of improper tense and voice, grammatical and spelling errors, plagiarism, and a lack of clarity. Consequently, poor writing skills were impacting upper-level chemistry courses. Students were focused more on report formatting and style than interpretation of data and scientific content.

Table 1. Student Demographics in Spring 2013, Fall 2013, and Spring 2014

Semester	*Spring 2013*	*Fall 2013*	*Spring 2014*
Class Size	116	260	140
Biology	53 (46%)	113 (43%)	62 (44%)
Chemistry	16 (14%)	62 (24%)	23 (16%)
Engineering	4 (3%)	12 (5%)	2 (1%)
Neuroscience	0 (0%)	18 (7%)	8 (6%)
Medically related[a]	6 (5%)	14 (5%)	10 (7%)
Other[b]	19 (16%)	24 (9%)	20 (14%)
Undeclared	19 (16%)	17 (7%)	15 (11%)

[a] Public Health, Medical Technology, Biomedical Sciences, Health Care Management, Nursing. [b] Physics, Mathematics, Psychology, Management, English, Physical Education.

These deficiencies led us to define three goals for changing the lab curriculum. First, we wanted the students to take a more active role in assessing and revising their work. In previous semesters, we allowed students to turn in a rough draft which the teaching assistants (TA) critiqued and returned for revision. However, the drafts were poorly written, and the final drafts often showed little improvement despite substantial feedback provided by the TA. Grading rough drafts and revisions with limited improvement added to the TA workload. Second, we wanted to reduce the number of formal lab reports allowing students time to develop technical writing skills through scaffolding and peer review. Finally, we wanted to institute systemic change in how students are taught to write, which would not only impact the organic chemistry lab, but also upper-division chemistry laboratory courses.

In order to achieve these goals, a scaffolding approach (*1*, *9*) was adopted to instruct students to write each section of a formal lab report. Along with the scaffolded writing assignments, peer review was added. Peer review has been shown to increase critical thinking skills, and has been widely used as a tool to develop technical writing skills (*10–15*). In general, peer review requires students to provide critical and detailed responses. It is not enough to say "I didn't like the way this was written"; student evaluators must think critically and provide a reason *why* the writing needs improvement. Peer review encourages students to become vested in the reviewing process; because they have expectations of others, they must hold their work to the same standard by which they assessed their fellow classmates.

All writing assignments were submitted electronically using Turnitin, a popular electronic plagiarism detection program currently in use at UAB. While we were concerned with plagiarism, the PeerMark feature of the program also allowed for online peer evaluation, similar to that of Calibrated Peer Review (CPR), an online program which allows for electronic submission and review of student work (*16–18*). Teaching assistants graded all writing assignments using the GradeMark component of Turnitin.

This is the first report on our efforts to use a scaffolding approach along with peer review to improve the writing skills in the undergraduate organic laboratory. The results reported reflect three semesters. We will describe implementation, assessment, and preliminary impact on writing in upper-division chemistry laboratory courses.

Implementation

In order to achieve the goals defined above, it was necessary to reduce the number of formal lab reports required without reducing the number of experiments. Students performed eight experiments during a 15 week semester and submitted eight formal group lab reports. The writing component of the lab was restructured, instituting more individual assignments that incorporated both peer and instructor feedback. Eight formal lab reports were reduced to four; three group reports and one individual report at the end of the semester (Table 2). In the modified version of the course, the experiments remained unchanged, but the writing assignments due for each experiment were redesigned with an emphasis on progressively developing writing skills. To this end, guidance and instructor feedback were abundantly provided in the early stages and then gradually decreased to promote the independence necessary for success in upper-division laboratory courses.

Scaffolding Approach

Four writing assignments were introduced, each of which focused on a separate section of a formal lab report. Division of the complete report into small writing assignments is referred to as a scaffolding approach. A similar approach has been previously implemented in lower level undergraduate laboratories and shown to improve development of proper lab report writing skills (*1*).

Following the first experiment of the semester, each student submitted an introduction. From the second experiment, an experimental section and graphical representation of data were submitted. The data and results from experiment three, and finally, from experiments four, the discussion and conclusion were submitted (Table 2). Prior to these changes, we found that when only group lab reports were submitted, the same student would write the same section of the lab report each week. With the scaffolding approach, each student builds a skill set, and can see evidence of both their deficiencies and improvements over time. Scaling back the initial writing load in the course allowed students to build up this skill set and to internalize feedback before incorporating it into complete reports.

Table 2. New Lab Curriculum Schedule

Exp. No	*Experiment Name*	*Writing Assignment*
1	Recrystallization and Melting Point	Introduction
2	Simple and Fractional Distillation	Experimental and Graphical Representation of Data
3	Thin Layer Chromatography	Data and Results
4	Extraction and Sublimation of Caffeine	Discussion and Conclusion
5	Kinetic Study of the Hydrolysis of t-Butyl Chloride	Group Full-Length Report
6	Alkenes from Alcohols to Alkyl Halides	Group Full-Length Report
7	Relative Reactivity of Alkyl Halides	Group Full-Length Report
8	Conversion of Alcohols to Alkyl Halides	Individual Full-Length Report

The assumption was that students were unfamiliar with formal scientific writing at the beginning of the Organic Chemistry I lab course; because of this, ample guidance and feedback were provided throughout. Improvement in writing does not happen without feedback and revision. If either is lacking, the same mistakes will be repeated. This is not surprising because if the student has no feedback and has achieved a grade that meets their expectation then they are left believing that what they have done is correct. Naturally, they repeat their mistakes. In our approach, we decided to combine the scaffolding approach with four additional guiding strategies to support students throughout the development of proper scientific writing skills. Guidance in the modified curriculum was provided in the form of an annotated writing sample, detailed rubrics, peer reviews, and instructor feedback. An annotated writing sample and the use of peer reviews and rubrics are guiding strategies implemented in other undergraduate laboratories to improve undergraduate scientific writing skills (*19*).

Using the work of Gragson and Hagen (*17*) as a template, we prepared a writing sample using a full-length lab report annotated throughout with instructions detailing the prominent features. The embedded instructions in this document, named the Integrated Writing Guide (IWG), state the objectives of each section in a summary paragraph followed by a checklist of key features that should be present in each section (*19*). Comments also pointed out the correct way to format tables, figures, and expressions. Figure 1A shows an excerpt from the IWG introduction with instructor commentary on the right hand margin. An example of one of the section checklists is shown in Figure 1B. Similar checklists were provided for each section of the report and for tables, expressions, and figures. An example of one of the figures from the IWG with instructor commentary and a checklist is shown in Figure 1C. The IWG, along with all other resource materials created for the revised course curriculum, were provided to the class for the entire length of the semester via the course website on

Blackboard. On the first day of class, students were made aware of all resources and TAs demonstrated how to access these resources. Students were additionally encouraged to frequently review the IWG throughout the course.

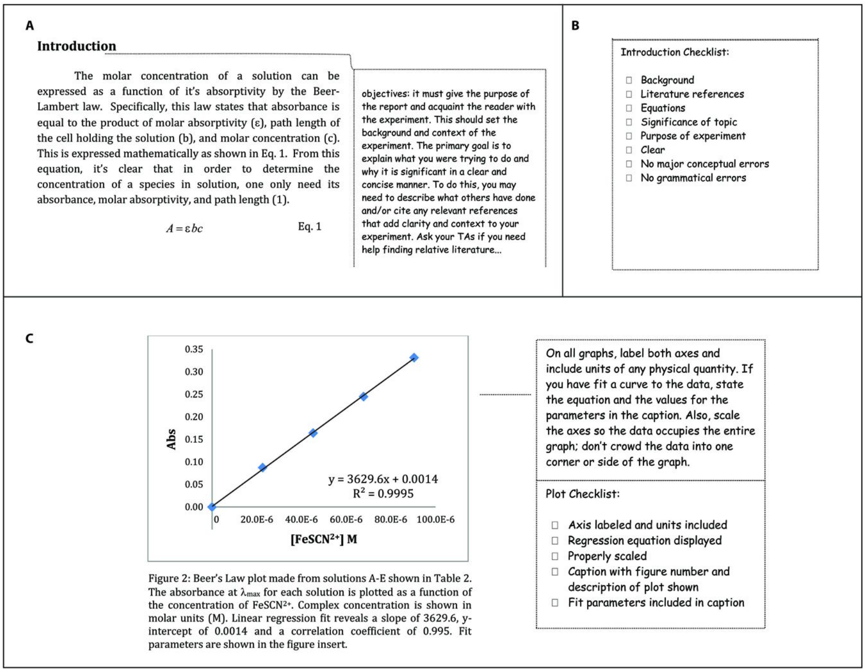

Figure 1. Excerpts from Integrated Writing Guide. An excerpt from a section of the sample lab report is shown (A) with embedded commentary on the margins. The commentary details the purpose of each section of the report and has a checklist of the prominent feature directly below the description. An example of the checklist provided for the introduction of the IWG is shown in panel B. Panel C shows the description and checklist provided for proper figure formatting in the IWG.

In addition to the IWG, detailed rubrics were provided for each of the first four short writing assignments and for the three group reports that followed (Table 2). Each rubric included the sections required for each assignment and listed the major concepts that should be included and/or addressed. An example of a writing assignment rubric is shown in Figure 2. Just like the IWG, students were frequently reminded how to access the rubrics for each assignment via Blackboard and were encouraged by TAs to use this resource, alongside the IWG, to guide the composition of the first four writing assignments.

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Recrystallization and Melting Point

Graded by:

Name:

		Good	Fair	Poor	Score
Introduction *(5 points)*	State the goal or purpose of recrystallization				
	Describe, generally (not step-by-step method), how recrystallization is performed				
	State the purpose of determining the melting point				
	Describe the effect of impurities on the melting point of a compound				
	Explain how mixed melting points are used				
	Show all chemical structures (drawn in chemsketch)				
	Figures are titled, numbered and have captions in complete sentences				
	Properly cited references (minimum of 3)				
	State the objective(s) of this experiment				
	No conceptual errors				
	No grammatical errors				
	Readability/ Conciseness				
Table of reagents *(1 pt)*	List name, MW, density, M.P., and B.P. of every chemical used				
	Proper table formatting; Properly labeled and titled				
References *(1 pts)*	ACS formatting				
	Credibility of sources				
	Listed in order of appearance in text				

Total ____________________

Figure 2. Writing Assignment Rubric. Shown is an example of the rubric for the writing assignment from the Recrystallization and Melting Point experiment. The rubric details which sections are required of this assignment, the point distribution, and details what needs to be included in each section.

Once written, assignments were submitted through Turnitin where they were automatically checked for originality. From previous teaching experience, we noticed many students had a difficult time understanding what constitutes plagiarism, so they committed academic dishonestly unintentionally. Copying text from referenced sources without including quotation marks and/or in-text citations and instances of self-plagiarism were commonly encountered mistakes. To address this, TAs provided instruction on how to properly reference and cite sources during the first day of class. A link to relevant excerpts from the ACS style referencing manual was made available to students via the course website. Students were also made aware of common plagiarism mistakes and strategies to avoid these mistakes were discussed. As a way of holding students accountable for the integrity of their submitted work, all writing assignments were subjected to the originality check feature of Turnitin.

Once assignments were submitted, they were randomly and anonymously distributed to the class for peer review through the PeerMark functionality of Turnitin. Each student was assigned up to three peer assignments for review. Peer reviews were guided with instructor prompts. PeerMark allows instructors to write their own questions to guide students' peer reviews. An example of the instructor prompts used to guide peer reviews for the first writing assignment is shown in Figure 3. A similar set of questions was provided for each of the writing assignments requiring peer reviews. In addition to answering these prompts, students were able to insert comments throughout each reviewed document. Although this was not a required part of the review, students were made aware of that option and were encouraged to use it. In addition, students were instructed to use the IWG and assignment rubrics as a guide through the review of their peers' work. Figure 4 shows three student responses to the peer review guiding question, "Could the readability, clarity, or style of this paper be improved? How?" (Figure 3). The comments panel in Figure 4 notes strength(s) and/or weakness(es) of each response.

Recrystallization and Melting Point	
1	Could the readability, clarity, or style of this paper be improved? How?
2	What concept was explained most clearly? Least clearly?
3	Are all tables and figures included and properly formatted in the style of the integrated writing guide? If not, explain what needs improvement/change.
4	Has the author missed anything that was required by the rubric? What items from the rubric would you recommend the author add/expand on?
5	How many references were cited? Do you believe the sources are credible? Are they formatted according to ACS guidelines?
6	Are the structures for all possible unknowns included?

Figure 3. Peer Review Guiding Questions. Shown are the questions provided for one of the writing assignments requiring peer reviews. These questions appeared on the PeerMark document created by Turnitin for each assigned review. Students were required to answer each question as they reviewed the document.

Student Responses	Comments
I think both readability and clarity can be improved, but I would first focus on content before diving in to presentation. Let's look at retooling each of your sections. Your reader should be able to identify one to three main points from each section. Put yourself in this reader's shoes. If you can't do the same, reconsider the purpose of each section.	• Reviewer notes improvement for clarity and readibility is needed and suggests ways to improve noted weakneses • The last sentence is not very clear and may not be understood by the author
Readibility- grammatical errors	• Grammatical errors are identified but there are no suggestions for improvements
The author needs to improve his/her paper, and arrange it.	• Reviewer notes improvement is needed but the feedback is too general and not actionable

Figure 4. Student Peer Review Examples. Example of student responses to the peer review leading question, "Could the readability, clarity, or style of this paper be improved? How?"

Worksheets

To assure that the learning objectives from each experiment were still being met, despite discontinuation of full-length reports, worksheets were assigned alongside the writing assignments. The content covered in the worksheets was meant to capture content not covered in writing assignments. For example, because the introduction was the focus of the writing assignment for the first experiment, the worksheet developed a description of the experimental design, analysis and discussion of results, and development of a conclusion. The first page of the worksheet assigned for the first experiment is shown in Figure 5. Due to the fact that experiments were conducted in groups, the worksheets were completed as a group effort. This encouraged students to collaborate on understanding the concepts and learning objectives of each experiment while individually developing their writing skills through the writing assignments.

Writing Cycle

Once students gained experience writing each section of the report individually and received ample feedback from peers and instructors on these sections, they were prepared to start writing full lab reports. Complete lab reports were assigned for the next three laboratory experiments (Table 2). Students completed each experiment and report as a group. Each group produced one report per experiment. This promoted the continuation of collaboration among group members for data acquisition and analysis as well as the organization and writing of complete reports. The students were required to write group reports using the writing cycle (*17*), with the review and revision processes used in preparing a scientific manuscript.

The writing cycle consisted of three roles: lead author, reviewer, and editor. The lead author was responsible for completing the first draft of the report. The initial draft was then submitted through Turnitin and forwarded to the reviewer who was responsible for critically reviewing the draft for content and format. After reviewing and commenting on each section of the report, the reviewer forwarded the reviewed report to the editor and submitted their comments through Turnitin. The editor was responsible for coordinating with both lead author and reviewer for accepting or rejecting suggested changes, and completing an edited version of the report. The finalized report was then submitted for a grade through Turnitin and e-mailed to the group, ensuring all participants had the final version. Separate Turnitin submission links for each role allowed instructors to track student participation. Individuals who did not complete or partially completed the assignment were penalized with point deductions from the graded submission. Students were instructed to cycle through these roles for each of the three reports. Since the writing cycle was used over three complete reports and students were organized into groups of three, each student in the group served in each role at least once. This rotation ensured that all students in the class gained experience in every aspect (writing, reviewing, and editing) of properly developing a complete report. Detailed rubrics were provided to assist students in both writing and reviewing efforts and they were encouraged to continue to use the IWG for report structure guidance.

CH236: Recrystallization and Melting Point

Names:____

Date: ________________________

OBJECTIVE (1 PT)

In 1-3 sentences, what will you determine from the results of this experiment?

TECHNIQUES (3 PTS)

Briefly describe the techniques used in this experiment.

Recrystallization: Why is it performed? How is it performed?

Melting Point: How is it used? What is the effect of an impurity? How is the Mixed Melting Point used?

EQUIPMENT AND MATERIALS (2 PTS)

List all equipment (including size of glassware) and reagents used in this experiment.

DATA/RESULTS (4 PTS)

Fill in the blanks using the data from your lab notebook. Include units where appropriate.

Unknown # ____________
Mass of unknown ____________
Volume H_2O used to dissolve unknown ______________
Mass of product ______________
Rough melting point of product (before drying)__________
Final melting point of product (after drying)____________
Mixed melting points

Compound mixed with unknown	Mixed Melting Point

Compound	Melting Point (°C)
Urea	133-135
Cinnamic acid	133-134
Salicylic acid	158-160
Acetanilide	113-115
Benzoic acid	121-123
Succinic acid	186-188

Figure 5. Worksheet Excerpt. An excerpt from the worksheet provided for the Recrystallization and Melting Point experiment.

The writing cycle was meant to build up three major aspects of student writing where we had historically noted deficiencies. First, because a single person was responsible for synthesizing a complete initial draft, the final report should have been a cohesive product, whereas reports in the past were composed by multiple authors piece-wise. As a result, the reports written prior to the changes described here read poorly and often communicated incomplete, or even contradictory, thoughts. Second, the writing cycle reinforced the importance of critically and thoroughly reviewing reports as a whole before submitting them for a grade. Lastly, completing and submitting complete reports forced the students to communicate, which developed peer collaboration and management skills. Peer collaboration additionally allowed for students to rely more on the support of their peers and less on instructor guidance, which was in line with our effort to gradually develop independence in student writing.

Individual Full-Length Report

The final experiment the students performed in the course was developed into a capstone writing experience. For this experiment, students were required to work independently with minimal guidance to complete one final, full-length report. By this time in the course, students had been guided with the IWG, detailed rubrics, peer feedback, peer collaboration, and instructor feedback through development of technical aspects of scientific writing and proper synthesis of critical analysis required of lab reports. In order to assess how well students could develop a complete lab report independently, and to prepare them to do so in upper-level laboratories, every student in the class was required to write a complete report for the final experiment in the lab (Table 2). As further motivation for students to acquire the necessary skills to perform well in the final report, this report was worth twice the number of points as the full-length group reports.

Assessment

Assessment focused on measuring gains in students' scientific writing skills. Statistical analyses included student performance on a written report for the same experiment before and after the implementation of the current curriculum, student performance during the semester, and student performance in future chemistry courses. Students were also surveyed using a variety of Likert scale style questions. Questions covered topics including the course generally, students' writing skills after completing the new curriculum, and the effectiveness of certain practices and tools used in the new curriculum.

Student Grades

One of the immediate goals of the current curriculum was to require students to a take an active role in assessing and revising their work. This outcome can be assessed most directly by examining the grades obtained on the full-length lab reports. Under the new curriculum, the first full-length lab report, completed as a group using the writing cycle, describes the "kinetic study of hydrolysis of t-butyl chloride" experiment in week five. This experiment was the fifth group lab report in the previous curriculum. The grades on the reports for the revised lab curriculum (Spring 2013, Fall 2013, and Spring 2014) were significantly higher than the grades for the reports from the previous curriculum (Spring 2011 to Fall 2012). Many of the earlier grade sheets did not separate the scores for the pre-lab (3 points) and the lab report (22 points) so grades were analyzed both excluding and including the pre-lab portion of the grade. Under the previous system, 197 students averaged 71% on the lab report alone while 665 students averaged 80% on the lab report and pre-lab together. Of 445 students who completed the course under the current design, the average grade on both the lab report and the combined pre-lab and lab report was 83%. This improvement in grade was statistically significant at the 95% confidence level using the z-test to test for differences in the means. This finding indicates that the goal of improving student writing was indeed being met.

Student grades on the first group lab report were compared to student grades on the third (final) group lab report. We wanted to determine whether the writing cycle was helping students make incremental, but significant, improvements across the group lab reports. While the grades for the third report (84.1%) were slightly higher than those for the first (83.7%), this difference was not statistically significant using the z-test. We propose that this rather constant performance across the group lab reports reflects the experience of each individual in a group serving in a different role each week. For each report there was a new lead author who had no experience being a lead author.

A longer term goal was to institute systemic changes in student writing that would impact the quality of writing submitted in upper-level labs. To assess progress on this goal, we considered whether the effects of the focus on developing writing skills in the first semester organic chemistry lab course (Organic Chemistry I lab) would carry on to future chemistry lab courses. The next course in the sequence is the second-semester organic chemistry lab (Organic Chemistry II lab). To investigate this hypothesis, grades for students who took the Organic Chemistry II lab in Fall 2013 and Spring 2014 were separated by the semester in which the student completed the Organic Chemistry I lab. No statistically significant differences were found using the z-test between the average writing grades of students who completed Organic Chemistry I lab under the previous and current curriculum designs. This result may be attributable to several reasons. First, it is possible that scientific writing skills were not developed in the Organic Chemistry I lab as intended, however the lab report grades stated above challenge this possible explanation. Second, while skills could be developed in the Organic Chemistry I lab, these skills may not be carried into the Organic Chemistry II lab. If students are not reminded or encouraged to continue using the tools and practices learned in Organic Chemistry I lab, they may revert to previous practices and lose the benefits gained in Organic Chemistry I lab. Finally, it is also possible that sufficient time has not passed to reliably use this metric for assessment. In the Organic Chemistry II lab, all lab reports are written by a group of three students and the groups are likely made up of students who have completed Organic Chemistry I lab in different semesters. As such, the group grade may not reflect the performance of the individuals, whose grades have been grouped by semester in which Organic Chemistry I lab was completed.

We plan to continue monitoring this metric over time. We would also like to collect data to determine whether the changes in the curriculum affect performance in analytical, inorganic, and physical chemistry labs. As noted in the introduction, only 20% of Organic Chemistry I lab students are chemistry majors. To date, there is not sufficient data to perform statistical analysis with respect to performance in the upper-level chemistry labs. Anecdotally, however, teaching assistants have noted that cases of exceptionally strong scientific writing tend to be produced by students who took the current Organic Chemistry I lab curriculum while examples of particularly poor scientific writing tend to be produced by students who took Organic Chemistry I lab under the previous curriculum or at another institution (personal communication).

Direct assessment of whether students become better scientific writers as a result of the current curriculum is difficult. Many factors are beyond our control and may impact the outcomes reported here. From a previous analysis comparing final grades across Spring, Summer, and Fall 2012 (before any of the changes discussed here were implemented), no statistically significant differences were found (using ANOVA) between the average final grades by semester or by teaching assistant, though there were some statistically significant differences in the variance of those final grades (Bartlett's test). Minimal differences in the means of different sections (ANOVA) were found in one semester such that a single outlier was identified, but identifying one outlier out of many sections is expected in such an analysis. These findings are noted here because we have reasonable expectation that differences in grades or grading based on the semester in which the course was taken or the TA who led a certain section are minimal. Still, it must be noted that many variables (including TA grading styles, weather related changes to the schedule, concurrent enrollment in lecture, etc.) cannot be controlled and could affect the results reported here.

One additional assessment strategy we plan to implement is a pre- and post-test. We will test students' scientific writing skills by way of brief analytical essays to be completed during the first week of lab and then during the final week of lab. We are currently working with a faculty member in the English department with expertise in "Writing Across the Curriculum."

Student Feedback

Students were surveyed on a number of factors related to the revised curriculum as a self-reporting measure of the students' ability to assess and revise their own work. Encouragingly, as shown in Figure 6, the overwhelming majority of students (82%, combined semesters) reported that their scientific writing skills improved across the course of the semester. When asked to self-assess the statement that "My writing skills are better now than they were at the beginning of the semester," 79% to 84% percent of students agreed or strongly agreed.

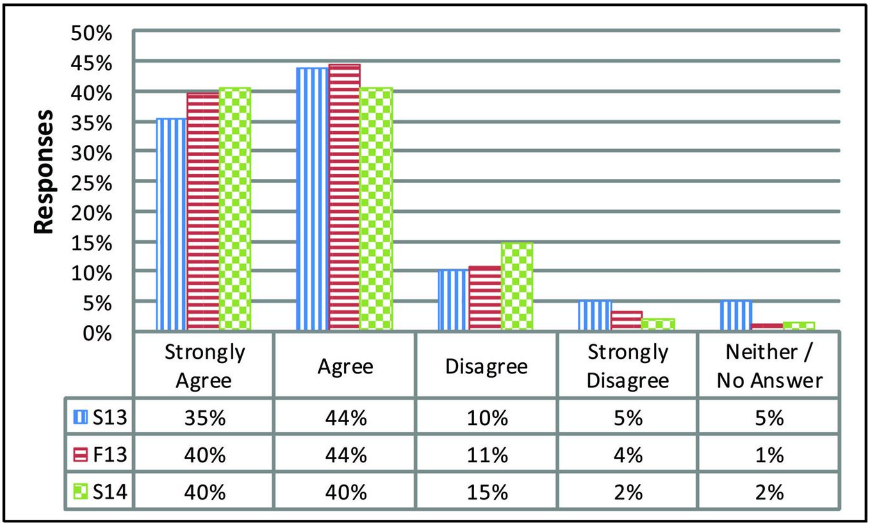
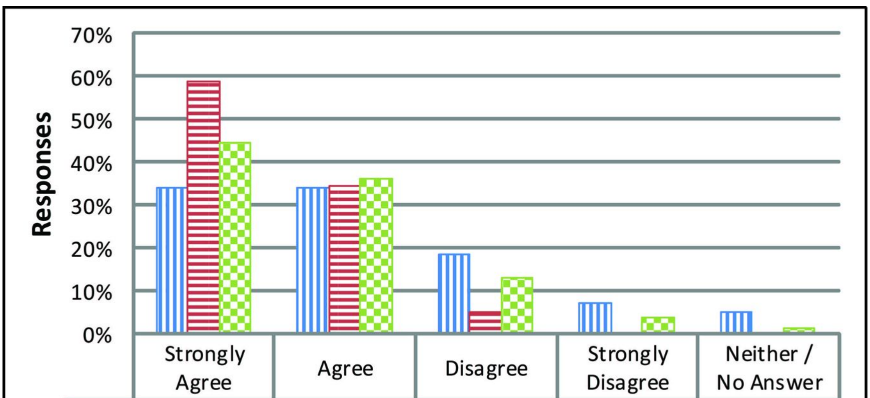


Figure 6. Student Responses for Improved Writing Skills. Responses from students who completed CH236, Organic Chemistry I Lab, in Spring 2013 (vertical lines), Fall 2013 (horizontal lines), and Spring 2014 (checkered). Students were asked to indicate how strongly they agreed or disagreed with the statement, "My writing skills are better now than they were at the beginning of the semester."

When asked about specific components of the curriculum, the "scaffolding approach" was identified as particularly helpful (85%, combined semesters). As shown in Figure 7, when asked to reflect on the statement that "The 'scaffolding approach' (focus on different parts of the report building up to writing a full report) was helpful in preparing me to write a full-length lab report," 94% percent of students agreed or strongly agreed in Fall 2013. The semester with the least positive student responses on this question, 68% of students agreed or strongly agreed with the previous statement, was the first semester in which the changes were implemented, Spring 2013. Among students who provided additional comments, the scaffolding approach was generally described as beneficial. For example, one student noted "the most helpful aspect of the course was breaking up the lab report into its parts to turn one [assignment] in each week. This way I didn't feel overwhelmed when I barely knew how to scientifically write."

When asked about another specific component of the curriculum, the "writing cycle," the student responses were more moderate, but still positive. As shown in Figure 8, a majority of students (66%, combined semesters) agreed or strongly agreed with the statement "The Writing Cycle (lead author, reviewer, editor roles) helped me learn to create and refine scientific writing." Students responding that they strongly agreed or agreed ranged from 50% to 70% by semester, again with the most negative responses observed during the semester in which the changes were first implemented, Spring 2013. Among students who provided additional feedback, most of the negative comments addressed difficulties with group work in general, rather than the writing cycle specifically. One student's memorable comment that "group work is the devil" seems to be a sentiment shared by several students. Group work is required in Organic Chemistry II lab, some of the upper-level chemistry labs, and labs in other STEM fields including biology and physics. Thus, while it may not be an enjoyable part of the experience, learning how to navigate group work is a crucial skill in college generally, in the sciences, and in most careers.

The peer reviews were described by students as a good idea, but poorly executed. We found that the quality of the drafts submitted varied widely and that the peer reviews of those drafts were often too general or brief to be helpful. This is a common problem with student peer reviews (*19*). For example one student commented, "The peer reviews were not helpful. I felt like I was wasting my time because a lot of people didn't try very hard on the first draft." While another stated, "It was a little aggravating at times when I would put in a great amount of effort in peer review and then would receive my paper back with comments like 'good.' This isn't very helpful when trying to edit, and also isn't very fair to the other student. For this reason, I think that identified reviewers would work better." The peer reviewers did not assign grades to the drafts as is done in CPR, and the peer reviewers were only penalized for failing to complete reviews, not for poorly executed reviews.



	Strongly Agree	Agree	Disagree	Strongly Disagree	Neither / No Answer
S13	34%	34%	19%	7%	5%
F13	59%	35%	5%	0%	0%
S14	45%	36%	13%	4%	2%

Figure 7. Student Responses for the Scaffolding Approach. Responses from students who completed CH236, Organic Chemistry I Lab, in Spring 2013 (vertical lines), Fall 2013 (horizontal lines), and Spring 2014 (checkered). Students were asked to indicate how strongly they agreed or disagreed with the statement, "The 'scaffolding approach' ... was helpful in preparing me to write a full-length lab report."

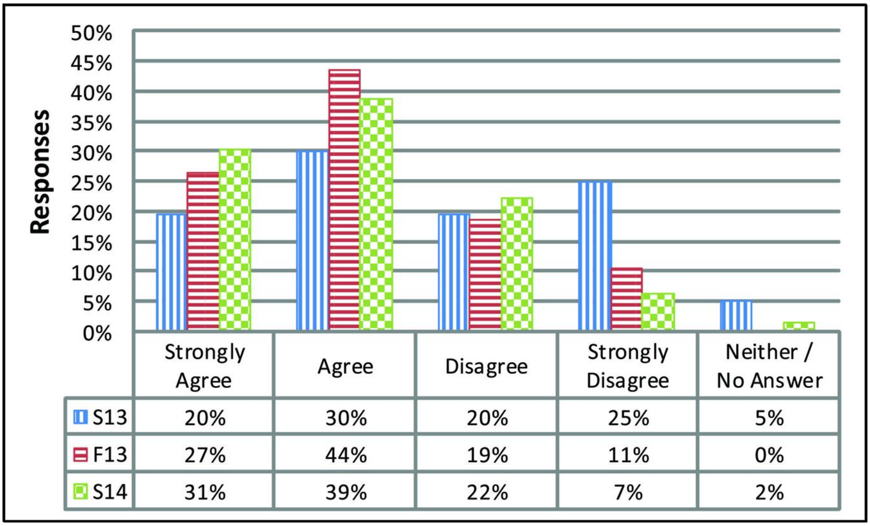


Figure 8. Student Responses for the Writing Cycle. Responses from Students who completed CH236, Organic Chemistry I Lab, in Spring 2013 (vertical lines), Fall 2013 (horizontal lines), and Spring 2014 (checkered). Students were asked to indicate how strongly they agreed or disagreed with the statement, "The Writing Cycle … helped me learn to create and refine scientific writing."

Despite these concerns, preliminary evidence suggests that peer reviews performed during the scaffolding portion of the lab have a significant and positive impact on the quality of the final, individual lab report. Recall that writing this report requires students to work independently (both without the input of their group members and without the guidance of a detailed rubric). In Spring 2013, all changes except the peer review (scaffolding approach and writing cycle) had been implemented. Peer review was then included in the Fall 2013 and Spring 2014 semesters. It should be noted that the final experiment was weighted differently in the Spring 2013 semester (35 points for the final experiment out of 500 total points in the semester) from the Fall 2013 and Spring 2014 (50 points out of 500 points), adding an additional variable which may have impacted student effort, and ultimately their performance, on this report. The grades on the individual lab reports were significantly higher in the semesters in which peer review was included (82%), compared to the semester in which peer review was not included (77%). This difference was statistically significant at the 95% confidence level using the z-test. Our findings compare favorably with those in the literature (*20*).

In many laboratory sections, students voiced concerns over instructor grades not being returned promptly. This issue is particularly important with respect to gaining the full benefit of the scaffolding approach. The qualitative feedback about the value of peer reviews and the timeliness of grading leads to a compounded, and unexpected, drawback to the current curriculum. While the number of assignments for the students has decreased, allowing them time to develop writing skills, the number of assignments a TA is responsible for grading has increased.

In the previous curriculum, a TA had 10 reports for each of eight experiments; now TAs must grade 30 individual assignments for the first four weeks, then 10 reports for three weeks, then finally 30 individual reports for the final assignment. During preparation of this curriculum, we anticipated that the peer review process would help students improve the writing submitted to TAs for grading, and thus would relieve some of the TAs' grading burden. This expectation has not been realized. The variability of peer review quality noted in student comments has been confirmed by teaching assistants. Since the peer review cycle has not yielded the expected improvement in student writing submissions, the time commitment of teaching assistants has unexpectedly increased. This situation can lead to an unfortunate backlog in grading, impairing the students' ability to implement corrections when completing successive assignments.

Conclusions

Students report that their writing skills have improved as a result of the revised curriculum, and the improvement in group lab report grades validates this observation. In general, the majority felt that the "scaffolding approach" was very beneficial, allowing them to work on each section of the formal report over a span of several weeks. Student opinion of peer reviewing in combination with the scaffolded writing assignments was still positive; however, most recognized that there were both pros and cons inherent to this method. The quality of the first draft was often so poor that student reviewers felt their effort was wasted. The quality of the reviews themselves varied; some were quite detailed while others gave no useful feedback to the author. Perhaps the reviewers should be graded on the quality of their reviews.

A consequence of the inconsistencies in peer reviews was an increase in the time TAs were taking to grade individual writing assignments. The expectation with peer reviews was that individual writing assignments would be more polished after peer review, thus requiring less scrutiny by the TA. This was not the case, and significant changes will be necessary in the peer reviewing process in future semesters.

Since the writing cycle was implemented for the group reports, the majority of negative comments were focused on group dynamics rather than the tool itself. While most students agreed that the writing cycle contributed to improvement of their scientific writing and editing skills, they also remarked that some group members did not take their role of author, editor, or reviewer seriously. We consider the ability to work with others to be an important life skill that all students should acquire regardless of their career plans.

One of the goals of the development of the new laboratory curriculum was to institute systemic change that impacted not only the organic laboratory program but also upper-division chemistry laboratory courses. We did not see a substantial change in the group lab report grades in the Organic Chemistry II lab during Fall 2013 or Spring 2014. This could be due to the fact that there were still a fair number of students enrolled in the second-semester lab that did not matriculate through the revised Organic Chemistry I lab course. Future plans include incorporation of the writing cycle into the Organic Chemistry II lab course. Ongoing assessment of report grades in both Organic Chemistry II lab and other upper-division chemistry courses is planned.

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Chapter 9

3D Printing in the Chemistry Curriculum: Inspiring Millennial Students To Be Creative Innovators

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Educators should certainly keep in mind the positive attributes of millennial learners as we consider new curricular approaches. In this spirit, a 3D printing in chemistry initiative has been undertaken at Stetson University that draws upon the technological prowess of millennial undergraduate students. 3D printing activities have been incorporated in the curriculum whereby students are challenged to create a variety of chemical models. Together, these activities represent a highly motivational means of getting students to further engage in chemistry, while at the same time practicing and demonstrating the skills of creativity/innovation, collaboration, and technological literacy deemed vital for 21st century professionals. The costs, compactness, low maintenance, and overall reliability of 3D printers have trended favorably in recent years to an extent that it is now possible to implement this technology within most academic settings. To the chemist, 3D printing represents a powerful new tool for creating more realistic, tangible models of molecular structures. 3D printing exercises can be incorporated in the curriculum as student lab assignments, out- of-class independent study or group projects for credit, or senior research projects. Several student projects are presented, ranging from the printing of simple ball-and-stick models of common chemical structures to the fabrication of more realistic, space- filling models of proteins and molecular complexes. The conversion of open-access, online Protein Data Bank (PDB) structures into 3D printed models and the use of quantum computational software to generate accurate structural representations of chemical complexes for 3D printing is also described. Several web and software resources that can be utilized by chemists in support of 3D printing activities, as well as other general purpose 3D graphics file creation and editing tools, are reviewed.

The Millennial Edge

The millennial generation has been inundated with information since birth, the flow of data delivered across an expanding number of media, internet, and other digital communication outlets. *Wired* at a young age, today's millennials have become increasingly wireless. Smartphone use for texting, social media, and other forms of wireless communication has been commonplace for several years. Together with growing tablet use, wireless connectivity is now accessible virtually every waking hour of the day (*1*). Armed with the latest gadgetry, teens and young adults have played a large role in ushering in a new wireless culture, where graphically enriched social exchanges can take place anywhere and at any time. While millennials solicit a portion of their digital information (e.g., Google searches, iTunes downloads, social media exchanges, or simply enjoying a DVD movie), far too much of the information stream has consisted of unsolicited advertising generated from a highly aggressive, global, consumer-driven economy. Years from now, a historian tasked with capturing the essence of the millennial age might very well characterize it as "one, never-ending sales pitch."

How has constant connectivity, the resultant flood of information, changes in the nature of social interactions, and the excesses of consumerism impacted and shaped the millennial learner? Undesirable characteristics that have been attributed to this upbringing include an increased prevalence of stress and anxiety, early exposure to unhealthy adult activities, and difficulties in forming healthy social pacts (*2–5*). The deluge of information has forced millennials to adopt more effective screening mechanisms. This adaptation to better filter may come with a price – shorter attention spans and less fortitude for exploring any one topic in sufficient depth. Taken together, these attributes are clearly detractors for learners and represent a challenge for 21st century educators.

Conversely, not all attributes of the millennial generation represent a negative (*3*, *5*). Many have argued that millennials are better multitaskers (*6*), more effective participants in a team work environment, and more accepting of constructive criticism - this last characteristic reinforced from years of receiving constant feedback in school and during childhood/early teen activities. Perhaps most notable, the technological proficiency of many millennial students is high and in many cases exceeds that of the instructors. As enthusiastic supporters of new technologies who possess a genuine desire to better understand the latest digital gadgetry, millennials are both motivated and well positioned to become the future innovators who will drive forward the technological components of our knowledge-based economy.

Educators should certainly keep in mind the positive attributes of the millennial generation as we design future learning strategies. In this chapter, a 3D printing initiative involving undergraduate chemistry students is described that draws upon the technological prowess of millennials. The project was undertaken during the 2013-14 academic year by students and faculty in the chemistry department at Stetson University, in collaboration with library faculty administering the Stetson duPont-Ball Library 3D Printing Innovation Lab.

What does 3D printing bring to the field of chemical education? Certainly an accurate three-dimensional visualization of how atoms are arranged within a structure is often required before one can truly understand a chemical's function. The value of hand-held, physical models in support of student learning is well documented in the education literature (*7–10*). While commercial model building kits have long been a great asset for students learning organic structure, most of these kits have limitations with regard to how they can be used to depict accurate bond lengths and angles (*11*). As will be demonstrated herein, 3D printing represents a powerful new tool that can be utilized by chemists to create more realistic, tangible models of molecular structures. 3D printing has only begun to be exploited as a resource by chemical educators. Readers are encouraged to consult two recent reports that document how 3D printing was used to render crystallographic information files (.cif) (*11*) and molecular potential energy surfaces (*12*). Chemical models created using 3D printing technology can do far more, however, than illustrate the basic structure of compounds. These models can be used to show how molecular entities bind and interact in a three-dimensional fashion (interactions that can be difficult for students to render accurately using traditional ball-and-stick model sets, or otherwise visualize using more abstract two-dimensional computer generated representations).

No longer just a toy of hobbyists, the decreasing costs, compactness, low maintenance, and overall reliability of 3D printers have trended favorably in recent years to the extent that it is now possible to implement this new technology within most academic settings. As part of the 3D printing initiative at Stetson, student-centered activities have been incorporated into the curriculum involving the creation of 3D printed models of common chemical structures. More elaborate projects have required students to use 3D printing in conjunction with existing quantum computational chemistry software to design more realistic, space- filling models of geometry optimized molecular complexes. Additional student projects have involved the conversion of open- access, online Protein Data Bank (PDB) information into 3D printed structures and the creation of geometry optimized 3D models of chiral host-guest complexes.

One of the most notable outcomes of the 3D printing initiative has been the tremendous enthusiasm of the students. The projects have provided a highly motivational, nontraditional outlet for students to not only grapple with important chemical principles, but to also practice skills that have been deemed critical for the 21st century workforce (*13*). Students who gained experience with the 3D printing methods early during the project eagerly shared their knowledge with classmates as new chemistry themed projects were undertaken. With minimal instruction from their faculty mentors, students mastered the necessary software tools and 3D printing hardware equipment, either through self-directed study or through collaboration with classmates.

3D Printing Technology

3D printing, also known as additive manufacturing, is an automated process of laying down successive layers of plastic or other manufacturing material to create a three-dimensional form (*14*, *15*). While technologies and equipment for additive manufacturing were first developed in the 1980s, only in recent years has commercial success been realized. In 1984, engineer Chuck Hull of Ultra Violet Products, California, invented the first additive manufacturing method that relied on UV laser curable photopolymers. After two years of refinement, Hull founded the company 3D Systems and patented the stereolithography method for rapid prototyping. Over the next two decades, inventors developed and patented an assortment of other 3D printing techniques, including Fused Deposition Modeling (FDM), 3D Inkjet Printing, Laminated Object Manufacturing (LOM), and Selective Laser Sintering (SLS). See reference sixteen (*16*) for a more detailed account of the history of 3D printing, as well as an appraisal of how these technologies are anticipated to impact biotechnology and the chemical science.

Among the various 3D printing methods that have been developed, FDM has emerged in recent years as one of the most affordable and widely used. Thanks in part to the recent expiration of the patent on this technology, several competing low-cost FDM 3D printers have been developed and brought to market. While the first generation of commercially available 3D printers would have cost tens of thousands of US dollars, a small desktop 3D printer can now be purchased at a price comparable to a common laptop computer. Expiration of patents aside, the prevalence of FDM printers in the marketplace is largely a result of a rapidly expanding open-source community which favors this equipment and which frequently shares user-created 3D designs over the web.

FDM printers, frequently referred to as extrusion deposition printers, use a thermoplastic which is extruded through a heated nozzle head, forming a small bead which quickly solidifies on the object under construction. Computer-aided manufacturing (CAM) software controls stepper motors that move the extrusion head around the build chamber, fabricating the object layer by layer.

Several different thermoplastics have been used for extrusion deposition, including acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), polyphenylsulfone (PPSU), high density polyethylene (HDPE), and various polymer blends. The thermoplastic is fed into the heated extrusion head as a thin filament. Filament plastic can be purchased in a variety of colors. Some 3D printers have multiple extrusion heads, making it possible to print in multiple colors. Figure 1 shows a typical two extrusion head 3D printer sold by MakerBot Industries.

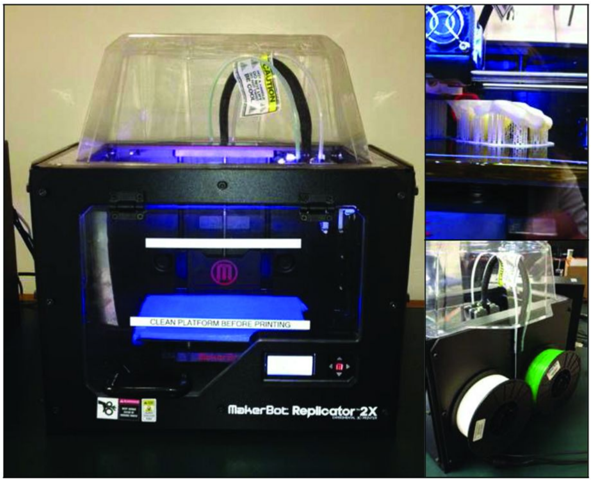

Figure 1. The MakerBot Replicator ™ 2X, shown on the left, a two extrusion head (two color) printer that was used during the Stetson chemistry 3D print initiative, is capable of 100 micrometer print resolution. The top right photo shows an active print job- both the raft and scaffolding support can be observed. Filament can be purchased in a variety of colors and feeds into the extrusion heads from large spools (shown in the bottom-right photo).

Common 3D Graphical File Formats

The design of a 3D printed object usually begins at the computer. The object of interest can be digitally drafted using any number of Computer Aided Design (CAD) programs (e.g., AutoCAD, AutoDesk, SolidWorks, and PTC Creo Parametric). Free-to-use, browser-based 3D design applications are also available for creating simple objects that can be printed outright or exported and subsequently edited using other applications. A variety of file formats have emerged in recent years for representing and sharing 3D computer graphics. Table 1 summarizes many of the formats commonly encountered in the 3D design and printing industry.

The most common input file format for 3D printing is an .stl file, where ‘stl’ stands for Standard Tessellation Language or STereoLithography. An .stl file defines the outermost geometry of a three-dimensional object as a triangulated surface, meaning the file contains the *x-y-z* coordinates of a sequence of connected triangular vertices that define the surface. The standard .stl file does not contain information about the color or texture of the surface. The spatial resolution of an object is limited only by the number of triangular vertices that make up the .stl file. Figure 2 shows an .stl graphical rendering of 2,2-dimethylpropane, where the triangular vertices are apparent on the carbon and hydrogen atoms that make up the structure.

Table 1. File formats commonly associated with 3D computer graphics design and printing.

File Extension	*File Format Name*	*Description*
.stl	Standard Tessellation Language or STereoLithography	Contains the coordinates of triangular vertices that define the surface; the most commonly used 3D printer file format.
.wrl (VRML)	Virtual Reality Modeling Language (VRML)	Format for representing 3D vector graphics in terms of polygon vertices and edges, as well as other object attributes; has been superseded by .x3d.
.x3d	Extensible 3D	Like .wrl but XML-based. Includes many extensions to VRML.
.obj	OBJ file	Defines simple geometric information (vertices, vertex normals, textures, characteristics of faces of each polygon) that make up a 3D graphic.
.iges	Initial Graphics Exchange Specification	Developed as a 'vendor neutral' means of 3D graphic digital exchange among CAD systems.
.dae	Collaborative Design Activity (COLLADA)	Open standard XML-based file format for transferring digital graphics between software applications.

Most commercially available 3D printers are now sold with an integrated software system that can accept as input .stl files, which allows for simple scaling and rotation of the object on the printer baseplate and handles all subsequent communication with the printer. Fortunate for chemists, little-to-no programming experience is required to accomplish printing. To print an .stl file, the software utilizes a series of algorithms that takes the .stl 3D mesh model and 'slices' it into 2D layers. The output of the slicer algorithm is a 'G-code' file that contains the specific instructions for moving the print head around the build chamber and extruding the filament to construct each layer.

While the .stl file contains only information about the surface of the object, the supporting 3D printer software will add an appropriate amount of plastic infill to stabilize the overall structure. For complex shapes, the software will also attach a 'raft' to the bottom side of a printed object so that it will better adhere to the baseplate. 'Scaffolding support' may also be added to help suspend and further stabilize irregular shaped portions of the object while it is printing. Raft and scaffolding support are visible in the active print job shown in Figure 1. The raft and scaffolding are both intended to be broken away from the main 3D object once it is printed. Some 3D printing plastic filaments, particularly ABS, can shrink a small amount after they are extruded and cool to room temperature. Significant shrinkage can cause the position of the extruder to get out of alignment with the latest printed layer, producing flaws in the printed object or an outright print failure. Increasing the percentage of infill in the 3D printed object can often rectify this problem.

3D graphical files can also be visibly captured using recently developed 3D scanning technology. The process uses as input a series of two-dimensional photographic images that are taken in a circle around the object in order to capture it from multiple angles. The photographs are analyzed using software algorithms that generate a 'point cloud' representing the object. A subsequent computational tessellation process is carried out on the point cloud that creates a solid surface 3D mesh that can be converted into an .stl file or alternative format. Vendors are now offering relatively inexpensive desktop 3D scanners and accompanying software (costing less than a thousand US dollars) that can capture moderately accurate computer graphic reproductions of objects. The entire process of generating a 3D graphical object from a sequence of two-dimensional photographs can also be accomplished through websites that utilize user uploaded photographs for that purpose, and also through mobile apps that utilize photographs captured directly using a smartphone or tablet camera.

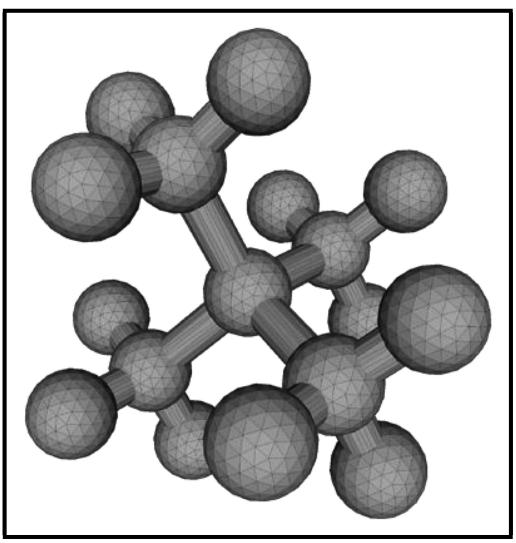

Figure 2. Example of a chemical structure, 2,2-dimethylpropane, rendered using the standard tessellation language (.stl) file format, where the vertices and sides of the triangles that define the surface are emphasized on the atoms.

Table 2. Chemical file formats utilized by many molecular modeling/visualization and computational chemistry packages.

File Extension	*Name*	*Description*
.pdb	RCSB - Protein Data Bank	Research Collaboratory for Structural Bioinformatics (RCSB) text file format for describing 3D information about biomolecules, including primary and secondary structure attributes.
.mol2	Tripos Mol2 file	Text file containing atom types, *x-y-z* coordinates of atoms, bonds, and connectivity, originally created for representing molecules within the SYBYL molecular modeling environment, but now common to most modeling packages.
.mol	Molecular Design Limited (MDL) Molfile	Text file containing atom types, *x-y-z* coordinates of atoms, bonds, and connectivity. Less common than .mol2.
.cif	Crystallographic Information File	Text file containing crystallographic information, promoted by the International Union of Crystallography (IUCr).
.cml	Chemical Markup Language	XML-based format for sharing a broad range of molecular information between web-based applications.
.xyz	XYZ file format	Text file containing number of atoms, molecular name, and Cartesian coordinates for each atom.

3D Printable Chemical Structures: Web-Based Resources and Software/Browser-Based Applications for 3D Graphics File Creation and Editing

Starting from scratch, how does one create a computer-generated, 3D printable chemical structure? One approach that is initially tempting, but which ultimately proves inefficient, involves using a CAD software environment to draw a ball-and-stick representation of the structure in question. The reader is encouraged to try this, drawing, for example, a simple molecule such as H_2O using a free CAD utility (*17*). It quickly becomes apparent that 'starting from scratch' and using a CAD program to draw even relatively simple organic molecules like the one illustrated in Figure 2 is extremely labor intensive, and is certainly not conducive to the creation of a geometrically accurate form.

Fortunately, a better approach exists. Chemists already have at their disposal any number of computer software applications for drawing 3D representations of molecular structures. Many of these applications include molecular mechanics and quantum geometry optimization routines capable of reproducing highly accurate bond lengths and bond angles for a structure. Unfortunately for the chemist who may wish to 3D print an optimized structure, presently available molecular modeling software packages are not yet able to export chemical structures in a format that can be directly 3D printed. Methods exist, however, to convert common molecular file formats into .stl and .x3d files that can be 3D printed. Several examples of how to accomplish these conversions will be detailed in the remainder of this chapter. Obtaining a 3D printable structure can often be done in one simple file conversion step. If the chemical structure needs to be edited in some fashion, the conversion may take more than one step.

Table 2 summarizes file formats that are common to many molecular modeling and computational chemistry software packages. To 3D print a chemical structure stored in one of these formats, the challenge becomes how to transform a 'molecular' file format to one of the standard '3D graphical' file formats listed in Table 1. Ideally this conversion should ultimately yield an .stl file which is recognizable by most commercially available 3D printers. The various file conversion methods that are described here are summarized within the flow diagram shown in Figure 3. The molecular modeling and visualization software resources along with the other web resources and computer software/browser-based applications that are referred in this flow diagram are described in more detail in Table 3. With the exception of a few commercial computational software packages (such as Gaussian, HyperChem, and Spartan), the applications and resources referred to in Table 3 can be downloaded or accessed for free. Consequently, little-to-no added expense is incurred to 3D print molecular structures beyond the initial investment in a 3D printer.

3D Printing Curricular Projects in Chemistry

What follows are several examples of student projects that have been carried out as part of Stetson's 3D printing initiative in chemistry. These exercises can be incorporated in the curriculum in a variety of ways: (1) as student lab assignments attached to a particular course, (2) as out-of-class group projects attached to a particular course, (3) as independent study assignments for credit, and (4) as individual senior research projects. As was mentioned in the introduction, students have exhibited a tremendous enthusiasm and initiative for carrying out these assignments, and have managed to do so in a mostly self-directed or peer collaborative fashion. Consequently, the projects represent a highly motivational means of getting students to engage in chemistry, while at the same time practicing and demonstrating the skills of creativity/innovation, collaboration, and technological literacy deemed vital for 21st century professionals. For each exercise, a list of web and software assets needed to complete the assignment (from Table 3) is given. The instructions provided will assume that the user has already downloaded/installed any software assets listed. The descriptions accompanying each exercise assume that the user has a 3D printer and supporting software that is capable of opening .stl files and which can be used to scale the size and orient the object prior to printing.

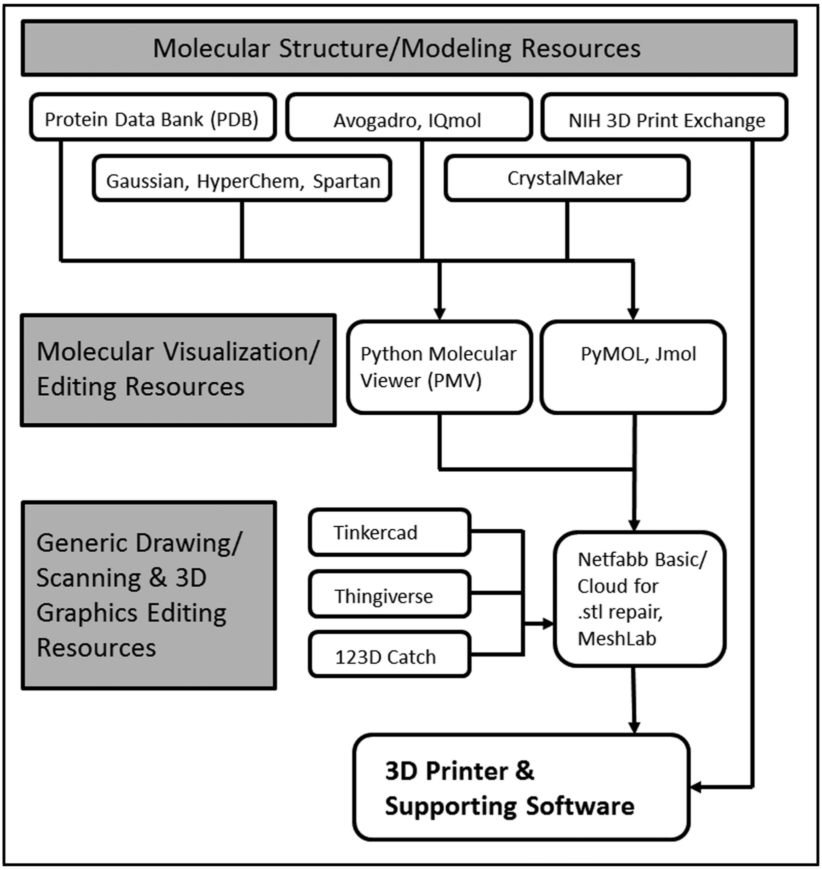

Figure 3. Flowchart illustrating how the various resources and applications listed in Table 3 can be used to generate 3D printable objects. Except in cases when significant intermediate editing is performed using PyMOL, Jmol, netfabb, or MeshLab, exported files from resources and applications can usually be 3D printed either outright or after only one file conversion.

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Table 3. Web resources and computer software/browser-based applications for retrieving, creating, and editing molecular structures, as well as other general purpose 3D graphics file creation and editing tools.

Name	*Free*	*Description*
Thingiverse (must create a user account)	Yes	Open-source, searchable, web resource for posting and sharing user-created 3D graphic files. Many chemical structures available to download and 3D print. Files can be downloaded in .stl format.
Protein Data Bank (PDB)	Yes	Searchable web repository for 3D structural data of biologically relevant molecules, maintained under the direction of the Research Collaboratory for Structural Bioinformatics (RCSB). Structures can be downloaded in .pdb format.
NIH 3D Print Exchange	Yes	Open-source, searchable, web resource sponsored by the U.S. National Institutes of Health (NIH) for posting and sharing biological/health related 3D graphics files. Many structures are derived from the RCSB - Protein Data Bank. Files can be exported in .x3d, .wrl, and .stl format.
Tinkercad (must create a user account)	Yes	Easy to use, browser-based 3D CAD design tool for creating simple prototypes. The utility can also be used to edit 3D graphics imported from other applications. Files can be exported in .stl, .obj, .x3d, and .wrl formats.
123D Catch (must create a user account)	Yes	Browser or mobile app-based 3D scanning application that transforms a series of user uploaded photos into a 3D computer graphic object. Files can be exported in .stl, .obj, and other formats. Account upgrade available for purchase.
Netfabb, MeshLab	Yes	Open-source, 3D mesh processing software. Useful for viewing, making basic edits to, and repairing previously created .stl files. Netfabb Basic is free. A pay version of Netfabb (Netfabb Cloud) is also available with expanded capabilities.
Python Molecular Viewer (PMV)	Yes	Molecular visualization software. Bonds and atoms can be rendered using lines, balls-and-sticks, and space-filling models (CPK). Supports .mol2 and .pdb input file formats. Structures can be exported in a 3D graphical .stl and .wrl file format. PMV is one of the most useful downloads for those wanting to convert chemical structure files into 3D printable files.
PyMOL	No	Molecular visualization software. Particularly useful for viewing/editing secondary – quaternary structures and for generating space-filling/surface renderings of structures with adjustable Van der Waal radii. Files can be exported in .wrl format. While not distributed as freeware, a single, noncommercial, educational copy can be requested.

Continued on next page.

Table 3. (Continued). Web resources and computer software/browser-based applications for retrieving, creating, and editing molecular structures, as well as other general purpose 3D graphics file creation and editing tools.

Name	*Free*	*Description*
Jmol	Yes	An open-source Java application for viewing chemical structures (*18*). Supports a broader range of chemical file formats than PyMOL. The Jmol suite includes a JmolApplet that runs in most web browsers, a standalone Jmol Application that runs on the desktop, and a JmolViewer that can be integratedinto other applications. The Jmol Application is particularly useful for converting less common chemical file formats (such as Gaussian Cube files) into 3D graphic .wrl files. Jmol does not currently export files in .stl format.
Avogadro, IQmol	Yes	Cross-platform software for creating and visualizing molecular structures. Molecular mechanics optimization. Structures can be exported in .mol, .cml, .mol2, .pdb, and other formats.
Gaussian/ GaussView, HyperChem, Spartan	No	Molecular modeling and computational chemistry software – molecular mechanics and quantum (semi- empirical, Hartree-Fock, DFT, other). GaussView is the graphical user interface that accompanies Gaussian. Structures can be exported in .mol2 or .pdb format.
ORCA, GAMESS	Yes	Quantum computational chemistry freeware – quantum (semi-empirical, Hartree-Fock, DFT, other). Not as user-friendly as Gaussian, HyperChem, or Spartan due to lack of graphical user interface. ORCA structures can be exported in .pdb format. GAMESS structures can be converted to .mol2 or .pdb format using Jmol. ORCA developed by F. Neese and collaborators, free for academic use. GAMESS (General Atomic and Molecular Electronic System), developed and maintained by the Iowa State University Quantum Chemistry Group.
CrystalMaker	No	Software for creating and visualizing crystalline structures. Structures can be exported in .pdb format.

1. Download and 3D Print a Previously Created, Public Domain Chemical Structure

[Web/software assets needed: Thingiverse or NIH 3D Print Exchange]

In many cases, someone has already done the hard work of creating a desired 3D printable model. Users around the world are sharing innumerable designs of chemical structures over the internet. ‘Thingiverse’ (thingiverse.com) has emerged as a popular website for sharing open source 3D printable designs, licensed under the GNU General Public License or Creative Common licenses. Entering the search term “chemistry” on Thingiverse will bring up many items that students can download as an .stl file and send straight to the 3D printer. Please note that it is often necessary to scale the overall size of a 3D print job so that it can be printed within a reasonable time period (a few hours). As a first project, a student might try searching and downloading “carbon nanotube structure” from Thingiverse. The ‘NIH 3D Print Exchange’ is another file sharing web resource that is dedicated to sharing biological/health related content. As the prevalence of 3D printing continues to grow in the upcoming years, no doubt many additional file sharing resources will become available as a resource for chemists.

2. Using Molecular Drawing Software (Freeware) To Create a Simple Compound for 3D Printing

[Web/software assets needed: Avogadro or IQmol; Python Molecular Viewer (PMV)]

While many molecular drawing tools require the purchase of a license, several reputable packages are available as downloadable freeware or that can otherwise be used freely for noncommercial, educational purposes. The 2,2-dimethylpropane (neopentane) structure shown in Figure 2 was drawn using a molecular drawing/visualization freeware called IQmol. As an initial exercise in creating a simple 3D printable structure, students can draw a compound of choice using either Avogadro or IQmol – both of these drawing tools can be found online and are free to download, and both include options for carrying out molecular mechanics geometry optimization. Once the student has created and optimized a structure, it can be saved either as a .mol2 or .pdb file. Once saved, the file should then be opened using the Python Molecular Viewer (PMV). In the PMV, the molecule can be rendered as a stick-and-ball structure by selecting ‘Display’ and then ‘Sticks and Balls.’ Setting stick radius and ball radii parameters to 0.5 and 0.7, respectively, should give rise to a ball- and-stick rendering that has enough girth to be structurally sound for 3D printing. Once a suitable appearance has been obtained for the chemical structure, the structure can be saved as an .stl file within the PMV by selecting that option within the ‘File’ menu.

Even though the PMV (and several other applications) are capable of creating an .stl file which can subsequently be opened and viewed on the computer, in practice these .stl files can often contain defects in the polygon mesh that will prohibit 3D printing (*11*). Attempts to 3D print a defective .stl file will usually result in a failed print job. Fortunately, readily available software applications can be used to detect defects in an .stl file and perform a repair prior to sending it to the 3D printer. The software resources netfabb (Basic or Cloud) and Meshlab have built-in defect detection algorithms and offer the user an option to repair the file. For this exercise and the others described hereafter, users are encouraged to check .stl files prior to 3D printing and perform repairs when needed.

3. Download and 3D Print a Biochemical Structure from the Protein Data Bank (PDB)

[Web/software assets needed: RCSB Protein Data Bank (PDB); Python Molecular Viewer (PMV); PyMOL (optional)]

A public web resource that is available for downloading biological macromolecular structures is the 'Protein Data Bank (PDB),' maintained by the Research Collaboratory for Structural Bioinformatics (RCSB). This searchable web repository includes more than 100,000 structures (as of 2014). Structures can be downloaded in a Protein Data Bank (.pdb) file format. Fortunately, it is relatively easy to convert a .pdb file into a 3D printable .stl format.

As an initial exercise in using the Protein Data Bank, students can go to the website, download, and subsequently 3D print a plastocyanin structure (see Figure 4). This protein is pedagogically instructive for introductory students of biochemistry because it provides an excellent example of a structure containing significant beta-pleated sheet contribution, with a minor amount of alpha-helix contribution. The details of the secondary structure of this protein are difficult to observe in ball-and-stick or space-filling models, but become apparent when the structure is rendered using a ribbon diagram. To generate and 3D print a ribbon diagram of plastocyanin, first open the .pdf file for this structure using the Python Molecular Viewer (PMV) and select the 'ribbon' display option. When selecting this display option, the user should also deselect other display options (such as *lines*, *sticks and balls*, *atomic spheres*, and *molecular surface* display formats). Once a ribbon structure for plastocyanin has been generated in the PMV, the structure can be saved as an .stl file and subsequently printed. Further refinements to the display properties of a biomolecular structure can be made using the software PyMOL. Although not as user-friendly as the PMV, PyMOL has enhanced adjustable display features that can become advantageous when trying to emphasize certain structural aspects of biological structures.

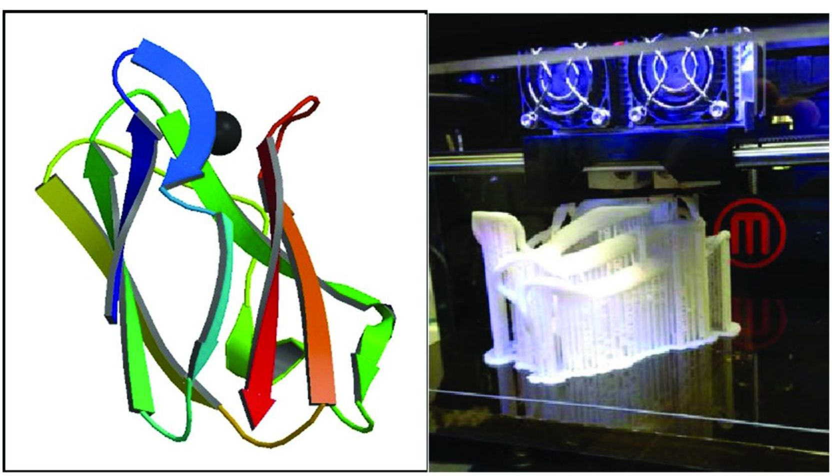

Figure 4. Ribbon structure of the protein plastocyanin (19) displayed as a computer graphic on the left and as an active 3D print job on the right.

4. Using Computational Chemistry Software To Create Optimized Structures of Fullerenes for 3D Printing

[Web/software assets needed: Gaussian, HyperChem, Spartan, or other computational software package that is capable of quantum ab initio or density functional theory (DFT) calculations; Python Molecular Viewer (PMV)]

Fullerenes represent a pedagogically intriguing class of carbon compounds that adopt spherical, ellipsoidal, and cylinder shapes. The spherical Buckminsterfullerene (or bucky-ball; C_{60}) is the most well-known example. Many quantum optimized structures of fullerenes are already available on the internet for download (these structures are usually found in a Gaussian output, .mol2, .pdb., or .xyz file format). As an exercise, students can use computational chemistry software to draw and optimize structures of different fullerenes for subsequent 3D printing. The C_{20} and C_{40} fullerene models shown in Figure 5 were created using the Gaussian 09 computational chemistry package [DFT, B3LYP level of theory with a 6-31G(d,p) basis set]. The Gaussian outputs were saved as .mol2 files, and subsequently converted to .stl files for 3D printing using the Python Molecular Viewer (PMV) according to the steps described in exercise 2 above.

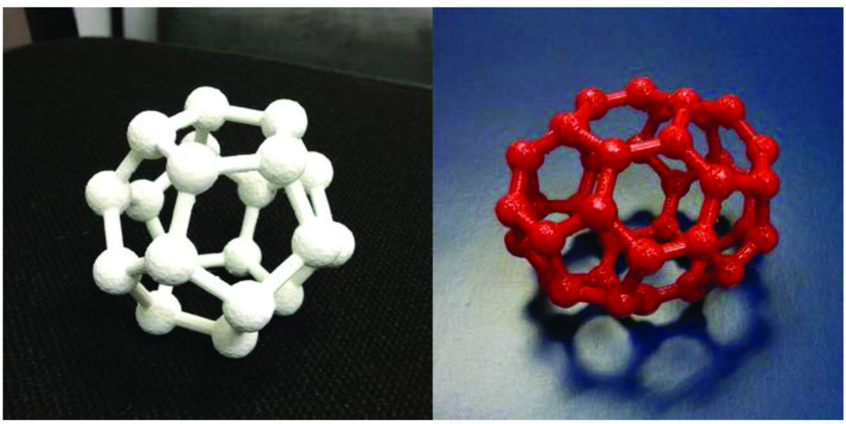

Figure 5. DFT optimized, 3D printed structures for the spherical C_{20} and ellipsoidal C_{40} fullerenes.

5. Using Tinkercad or Gaussian To Create Atomic/Molecular Orbital Models for 3D Printing

[Web/software assets needed: Tinkercad (for drawing simple atomic orbitals); Gaussian, Jmol, and Meshlab/netfabb Basic (for creating molecular orbitals)]

As an example in using a relatively simple, free CAD drawing environment, students can create models of atomic orbitals using the online, browser-based Tinkercad application (tinkercad.com). A user account must be created to access this utility. Shown in Figure 6 is a d_{yz} atomic orbital model drafted using a combination of cone, sphere, and cylinder shapes within Tinkercad. The final Tinkercad design can be downloaded as an .stl file and sent directly to the 3D printer.

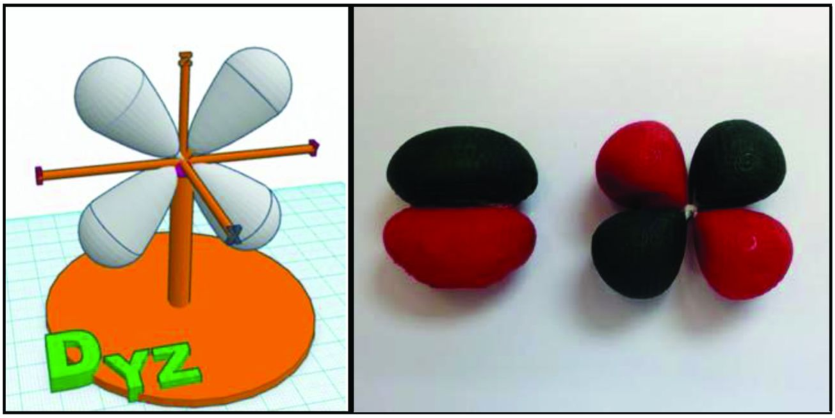

Figure 6. d_{yz} atomic orbital model screenshot from Tinkercad shown on the left. On the right are shown molecular orbitals for ethylene (HOMO and LUMO), calculated in Gaussian and 3D printed, with opposite lobes painted red and black.

More challenging, students can 3D print molecular orbitals that have been created using quantum computational chemistry software. Gaussian can be used as a starting point to for this purpose. Briefly, students first need to carry out a quantum level single-point or geometry optimization on a molecule of interest in order to obtain the Gaussian checkpoint (output) file. Opening the checkpoint file using GaussView, each molecular orbital associated with the calculation can be visualized and saved as a Gaussian Cube file (.cub extension). Jmol Application can then be employed to open and view .cub files, and 'WRITE' them as .wrl files (*18*). Meshlab and/or netfabb Basic can subsequently be used to edit the resultant .wrl files and convert them to .stl files for 3D printing. In this fashion, students created the HOMO and LUMO models of ethylene shown in Figure 6.

6. Using Computational Chemistry Software To Create and Optimize Compounds and a Host-Guest Complex for 3D Printing

[Web/software assets needed: Gaussian, HyperChem, Spartan, or other computational software package that is capable of quantum semi-empirical, ab initio, or density functional theory (DFT) calculations on molecular structures; Python Molecular Viewer (PMV); PyMOL (optional)]

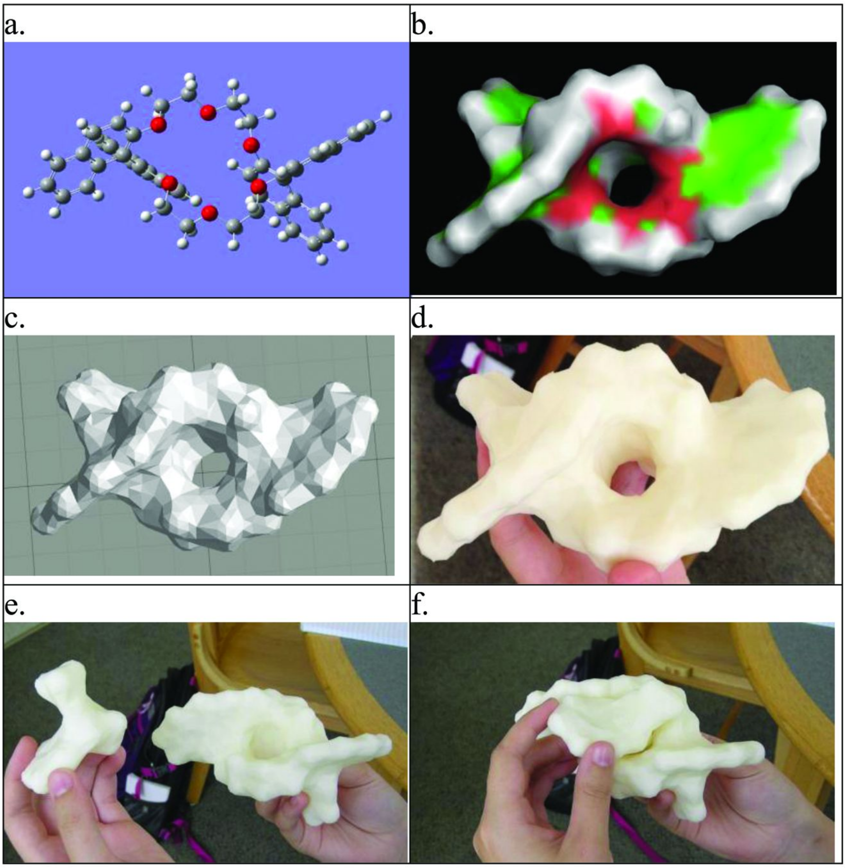

Figure 7. Step-by-step creation, from top-left to bottom-right, of a 3D model of a chiral recognition complex; (a) a ball-and-stick model of the host complex is created and optimized using the Gaussian 09 software; (b) the optimized complex is converted into a space-filling 3D model using the molecular visualization software PyMOL; (c) the space-filling model is converted into a 3D printable file using MeshLab; (d) the final printed form of the host complex; and (e-f) a demonstration showing how the molecular host complex binds one chiral isomer of the amino acid structure (phenylglycine methyl ester ammonium cation).

To calculate the most accurate geometry of a molecule prior to 3D printing, students can make use of any number of computational chemistry software tools. Most user-friendly quantum-capable computational utilities are commercial. A few packages exist that can be downloaded as freeware, although these applications typically lack a graphical user interface for drawing molecules and setting up calculations, and therefore they are not as user-friendly. Most packages allow the user to save/export optimized structures using one of the common chemical file formats listed in Table 2. Python Molecular Viewer (PMV) can subsequently be used to alter the rendering of the structure and convert it to an

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.stl file for 3D printing. Alternatively, PyMOL can be used to create various space-filling renderings of the structure prior to printing.

The opportunities for chemistry-themed student projects would seem endless considering the many different levels of theory available for modeling structures. Molecular mechanics can be used to model protein structures, semi-empirical or ab-initio methods can be used to model simple organic structures, or DFT methods can be employed to investigate the structure of more elaborate transition metal or host-guest complexes.

One project carried out by a Stetson student has shed new light on seminal Nobel Prize winning work undertaken by Dr. Donald Cram (UCLA) in the 1970s and 1980s. A chiral recognition host-guest complex model was created using a combination of quantum DFT computer calculations and 3D printing. The host complex selected, consisting of a crown ether–1,1′-dinaphthyl structure which was synthesized and studied by Cram and coworkers in the 1970s (*20*), was shown during these earlier studies to be enantioselective toward binding one isomer of phenylglycine methyl ester ammonium cation. This particular binding interaction was modeled by a senior chemistry student as part of Stetson's 3D printing initiative, using the Gaussian 09 computational chemistry package [DFT, B3LYP level of theory with a 6-31G(d,p) basis set] to optimize the geometry of the host, guest, and the host-guest complex. The progression of steps associated with creating the 3D printed model of this host-guest complex is illustrated in Figure 7.

As proposed in Cram's original work, the student's computational results revealed three-points of binding between the host and guest, occurring due to hydrogen-bonding interactions between the three hydrogen atoms of the ammonium group (guest) and three separate oxygen atoms associated with the central crown ether (host). The combination of a pocket on one side of the central crown and a steric barrier on the opposite side is what leads to the chiral selectivity. The 3D printed models of the host and the *R* and *S* isomers of the guest can be used to demonstrate how one isomer fits nicely in the binding pocket whereas the other isomer is sterically hindered (illustrated in the bottom two photos in Figure 7). The results of this student project suggest that the selective binding that occurs in this host-guest complex is restricted to only one side of the host because of a lack of D_2 symmetry in the energetically favored conformation. Cram's original work implied equivalent binding pockets on the top and bottom sides of the host complex due to assumed D_2 symmetry (*20*).

7. Using Crystalmaker To Create Unit Cell Representations of Cubic Lattices for 3D Printing

[Web/software assets needed: Crystalmaker; Python Molecular Viewer (PMV); Tinkercad]

Students encounter cubic crystal lattices as early as general chemistry. 3D printed models of these crystals can prove useful in helping students visualize and differentiate attributes associated with simple, body-centered, and face-centered lattices. As an exercise, students can use the software Crystalmaker to generate cubic and other lattices that can be 3D printed. For each crystal class, the

Crystalmaker lattice can be exported as a .pdb file and subsequently opened using the Python Molecular Viewer (PMV). To model cubic-close-packed arrangements, the 'ball radii' should be increased within the PMV so that the atomic spheres are touching. The file can be subsequently exported as an .stl file. This file can be 3D printed outright. To create a unit cell, however, students can import the .stl file into Tinkercad. Cropping options in Tinkercad can be used to cut away half of the atoms on each unit cell face before exporting the .stl file for 3D printing. In this fashion, students were able to create the crystals shown in Figure 8.

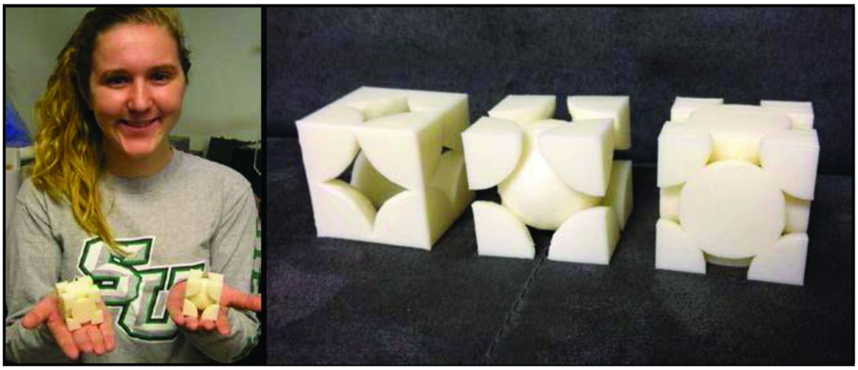

Figure 8. Simple (primitive) cubic, body-centered cubic (bcc), and face-centered cubic (fcc) crystal lattices created using the software Crystalmaker and subsequently edited using PMV and Tinkercad prior to 3D printing.

8. Using Mathematica To Print a Physical Model of a Mathematical Function

[Web/software assets needed: Mathematica]

While a number of examples have been presented here that illustrate how 3D printing can enhance student engagement and learning in chemistry, no doubt this technology has the potential to impact other academic disciplines. As an example of how 3D printing can be incorporated in the mathematics curriculum, students can use this technology to create a physical model of a mathematical function. To accomplish this task, the student can make use of the software application Mathematica to generate a 3D graphical rendering of the function

$$F(\theta,\phi) = 1 + \frac{Sin(5\phi)}{5}, \quad \text{(Equation 1)}$$

plotting the function over the range $\theta = 0$ to π and $\phi = 0$ to 2π. Fortunately, Mathematica now supports exporting most 3D graphical content in an .stl format. In this fashion, the mathematical spheroid model illustrated in Figure 9 was generated.

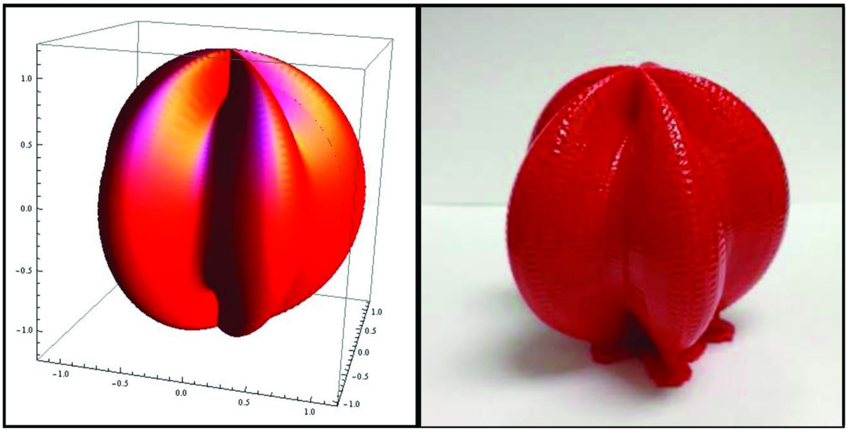

Figure 9. Mathematical equation (1) rendered as a 3D spherical coordinate contour plot within Mathematica (left) and subsequently 3D printed (right). In this example, the raft was left on the 3D printed object so that it would have a base.

Conclusion

The number of open-source, noncommercial web and computer- based software applications available for creating, editing, and sharing 3D graphical files has grown tremendously over the last few years. This rapid expansion has no doubt been fueled by innovative developments in low cost, reliable 3D printing. When these resources are used in conjunction with existing chemical drawing and modeling software, as has been demonstrated herein, they represent a valuable collection that empowers chemists to better visualize and grasp the intricacies of the chemical world. The fact that so many of these applications are heavily used, promoted, and shared by advocates of the open source movement means that many of these resources are likely to remain free to use. Consequently, the primary expense in establishing and maintaining a 3D printer in support of chemistry curricula and other academic programs will remain low, consisting primarily of the cost of the printer and accompanying filament.

Acknowledgments

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Chapter 10

Approaches for Increasing Professor Accessibility in the Millennial Classroom

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A defining characteristic of the millennial college student is their burden of significant off-campus responsibilities such as work and childcare. Campuses have responded to the needs of these students by utilizing technological advances to move many classes, and sometimes entire degree programs, online. While many schools have online chemistry courses for freshmen courses and non-chemistry majors, chemistry programs have been largely left behind in the world of online courses. This has left many of our students with less flexibility in their curriculum than in many other non-science disciplines. One consequence is that many students are unable to access their chemistry instructor for office hours, review sessions, and other in-person forms of communication outside of class. Presented here is a summary of methods that can be used to increase accessibility and maximize the effectiveness of student-instructor interactions using email, popular social media resources, learning management systems, web conferencing programs, and desktop streaming software.

The Changing Classroom

Perhaps it is a great understatement to say that technology has revolutionized the college experience. We have reached the point where our traditional students, born in the middle 1990's, have never known a time before web-based course options, electronic course registration, e-books, online homework, digital journals, and PowerPoint presentations. They can answer their own questions in class by

In Addressing the Millennial Student in Undergraduate Chemistry; Dockery, et al.;

looking up answers in seconds on a smartphone. They can do extensive literature searches from home or even a local cafe. To put this into context, the average college professor is around 50 years old, and would have been in college from the early 1980's through the early 1990's (*1*). They would have been students during a time where household computers, internet, and cell phones simply did not exist on any large-scale commercial production. It is easy to see that the college experience for our millennial students is radically different from that of the majority of their professors.

It could be argued that the most significant impact that recent technology has brought to academia is how professors can interact with their students. It has been many years since students had little choice but to form a long line outside of a professor's office for help during limited office hours. Now, acquiring the help of a professor is as easy as using a smartphone, tablet, or computer to quickly email questions. This has liberated both the students and their professors as an interaction can be timed to when both individuals are available. This is becoming a necessity as more of our students are finding themselves attached to significant responsibilities outside of the classroom and off-campus.

As the face of the modern college classroom has been changing in response to more available technologies, the face of the average student has been changing as well; this is illustrated in Table 1. In a trend that has been progressing for several decades, there are more high school seniors pursuing college after graduation (*2*), there are now more ethnic minorities than ever before in college (*3*), and there are generally more women on campuses earning degrees (and in many schools outpacing the number of male graduates) (*4*). Other significant changes in the student population are with regard to age and income level. Students from less affluent families are now entering college in larger numbers and there are more students meeting "non-traditional" student criteria (*5*). Recent figures show that 71% of students are now taking out student loans, with the average student loan debt for a bachelor's degree being $29,400 (*6*). Perhaps unsurprisingly, our millennial students are continuing the trend started by Generation X students and are seeking significant external employment as they financially support themselves and sometimes their familes (*7*). This is best illustrated in Figure 1, where the employment status of full-time millennial and Generation X students is higher than in the baby boomers before them. When looking at full-time students, there has been a steady decrease in students working less than 20 hours/week while the number of students working over 35 hours/week has been increasing. During the Great Recession, employment across all groups fell, but comparing millennial students before the recession to the baby boomer generation of most of their professors', there is a significant difference in the amount of work these students are putting in outside of the classroom at their place of employment.

The demographic changes in our classrooms have led to an increasing number of students needing flexibility in their school schedule, as their other work and family obligations may not offer much in terms of flexibility. Colleges have responded with online classes, night classes, terms outside of the traditional fall and spring, hybrid classes, and, in some cases, weekend classes. While chemistry programs (and other lab-based disciplines) have been largely unable to move online exclusively, there are still ways that we, as chemistry professors, can utilize some of the newer online technologies to increase the flexibility of our classes; ultimately, this will better suit our students' schedules. This can have the ultimate outcome of helping students with significant off-campus responsibilities have a better chance of thriving throughout their academic career and directly influence their quality of life post-graduation. Presented here are some representative technologies that can be used in both conventional and unconventional ways in the millennial classroom. The ultimate goal of using these is to promote a more flexible, accommodating environment for our students through increased professor accessibility.

Table 1. Demographic changes on American college campuses between 1990 and 2012 (*2–5*, *7–10*).

	1990	*2012*
Percent of All Adults (20-21)[a] in College	39.7%	54.0%
Percent of Adults (20-21)[a] that Attend College (by Race)	41.3% (White) 28.3% (Black) 27.2% (Hispanic)	55.9% (White) 50.7% (Black) 47.5% (Hispanic)
Percent of Adults that Attend College (by Gender)	58.0% (Male) 61.3% (Female)	62.2% (Male) 71.3% (Female)
Percent of Students Using Financial Aid	54.7%	67.4%
Percent of College Students Over 24	15.5%	21.5%

[a] Ages of 20-21 were chosen to eliminate students in the 18-19 demographic who could be enrolled in either high school or college.

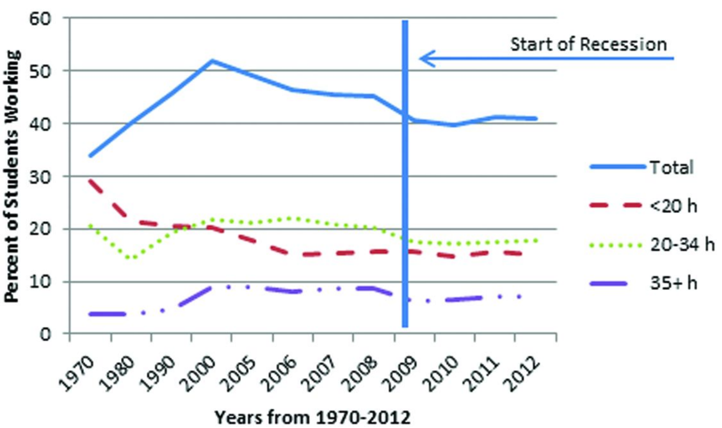


Figure 1. Percent of Full-Time Students with Employment in Hours per Week, Selected Years from 1970-2012 (3)

Portable Electronic Devices

The use of electronic devices is ubiquitous in college students, though the types of preferred devices vary from individual to individual. Of particular interest are devices that can work as a small portable computer, such as tablet computers (e.g. Apple iPads, Google Nexus), laptop computers, and smartphones. Many of the portable electronic devices available commercially have potentially useful applications inside and outside of the classroom, and the literature are replete with classroom uses for these electronics. Frequent academic uses for these include problem solving, lab experiments, homework assignments, and access to e-books (*11–17*). Generally, these devices have similar capabilities, but will be addressed separately here to clarify the consumer base for each. Table 2 provides a list of relevant devices and their consumer percentages among college students.

Table 2. Percent of college students owning selected portable electronic devices in 2013 (*18*)

Device	*Percent Owned*
Tablet computer	*36%*
Cell Phone (adults ages 18-24)	69% (Smartphone) 33% (Non-Smartphone)
Personal Computer (enrolled in college)	85% (Laptop Model) 48% (Desktop Model)

Tablet Computers

The ownership of tablets has been increasing rapidly since 2010, when the first models were released. They are now used frequently in the K-12 school system to keep young students engaged in learning and are a fun device for adults wanting to use their various applications. The primary issue with using tablets for classroom accessibility and flexibility purposes in a college setting is that most college students still do not own them. Recent figures show that 36% of college students owned a tablet in 2013 (*18*). While that figure is likely to continue to increase quickly, we cannot currently assume all college students have access to tablet technology outside of where they may be provided in our classrooms.

Smartphones

Generally with the same capabilities as tablets but with a smaller size, smartphones are convenient and practical in terms of portable technology. Recent studies have nearly 100% of college students owning some type of cell phone, and 69% owning smartphones (*18*). However, ownership of smartphones depends largely on factors such as socioeconomic status (*19*). While the majority of college-aged students own a smartphone, these figures may not be representative of all student groups, especially at college campuses with high numbers of minority students, those that are economically disadvantaged, or those in two-year institutions (*19*).

Laptop Computers

Last but not least, laptop computers have been and continue to be a fixture in college students' lives. These are perhaps the most versatile of the portable devices as they have the fastest speeds, most storage memory, and most useful programs for completing assignments. While tablets and smartphones are great for using internet resources through downloadable applications, laptop computers have a superior ability to run word processing, chemical drawing, presentation, and spreadsheet software. They have higher powered processing capabilities for multitasking. In comparison to tablet and smartphone applications, computer programs generally work without the need to be connected to Wi-Fi to function (this is excluding Google Chromebook laptops, which function more like a tablet than a standard laptop). The flexibility of a laptop computer is why it continues to be the workhorse device for college students, with 85% owning a laptop in 2013 (*18*).

Concluding Points

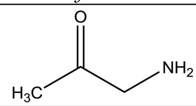
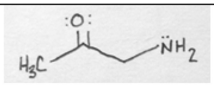
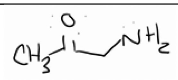
With the figures presented above, it is easy to see that when looking at the sum of all devices the vast majority of college students have access to some sort of portable technology. In many cases, students own more than one device, including ones with redundant functions. What all of these devices have in common are email and internet capabilities. With few exceptions, they also have cameras, video recording capabilities, speakers, and microphones. These features in particular make portable devices ideal for remote communication between students and their professors.

Maximizing Faculty-Student Interactions through Email

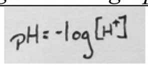
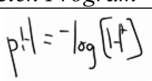
It seems that the pinnacle of accessibility has come by way of email. Students and faculty alike can send messages through computers, tablets, and smartphones. Students can send questions from study groups in the library or from home in the middle of the night and faculty can respond when they are available. Essentially, email has the ability to act as extended office hours when faculty are away from the office and classroom. There are some pretty obvious limitations to using email, especially in chemistry. While some questions are quite straightforward and can easily be asked and answered in a typed message format, the majority of our problems call for use of characters other than standard alphanumeric. Email servers are not equipped to enter and deal with mathematical equations or chemical structures, therefore standard email communication can be quite ineffective in our field. It can become quite the annoyance for students, who through no fault of their own, cannot communicate their thoughts, ideas, and questions to their professors using standard email for communication. There are ways, however, to increase the abilities of email to make it more chemistry-friendly. Most importantly, students have the ability to attach files to their emailed questions. This allows them to add image files that show exactly what their question is addressing. As seen in Table 3, there are several viable options for these files that do not require the purchase of any additional software or applications, and that are compatible with the device(s) owned by most students.

Table 3. A visual comparison of different drawing methods for chemical structures and mathematical equations

Representative Chemical Structures

Program	*Chemistry Software*[a]	*Digital Photograph*[b]	*Sketch Program*[c]
Example			
Ease of Use	Difficult	Easy	Moderate
Readability	High	High	Depends on User

Representative Mathematical Equations

Program	*Equation Editor*[d]	*Digital Photograph*	*Sketch Program*
Example	$pH = -\log[H^+]$		
Ease of Use	Difficult	Easy	Moderate
Readability	High	High	Depends on user

[a]ACD ChemSketch used. [b]Smartphone camera used. The darker background is typical for this method. [c]SketchBook Express on a Google Nexus 10 tablet used without a stylus. The disconnected lines are common for this method when used with or without a stylus. [d]Microsoft Word equation editor used.

Equation Editor Software

For emailing mathematical equations, students can use math equation editors. If a student has access to a word processing program like Microsoft Word on their computer (or any campus computer), they can type mathematical equations using the "insert equation" function and attach the file in an email to their professor. Typing out equations can be quite cumbersome and time- intensive, however, so the times where this is the most useful are when students have a very simple question or when they are already typing equations out, such as for a lab report or term paper. Also, while a minority, there are still students who own no portable technology and rely exclusively on the computer resources of their university. This method would work well for these students as it may be the only option they have available to them with the existing software on campus computers. For students who prefer to use tablets or smartphones, there are also similar free, downloadable math equation editor applications such as MathMagic. These programs can be used to type out mathematical equations that can then be emailed as an image file directly from the device.

Chemical Drawing Software

Another issue particular to chemistry is that of sending chemical structures. Drawing chemical structures digitally poses its own set of problems because it cannot be done in standard word processing software. Students can download free chemical drawing software like ACD ChemSketch that they can use to put together structures and reaction schemes, but this can also be quite time- intensive, especially for sophomore students just entering organic chemistry. Arrows not in the exact right location can make or break the correct answer, and it can be difficult for faculty to assess whether a student has the correct answer if their arrows or electrons are slightly off due to poor digital drawing skills. Chemical drawing software does remain useful when students are more advanced in their studies and can use the software more quickly, or, once again, when they already have the question typed as part of a lab report or other assignment. Chemical drawing applications such as ChemDoodle also exist for use in tablets and smartphones, and students with these devices could use these to send digital images to their professor. A main issue with these programs is that they require an initial purchase; they are quite a costly investment to students, especially those who are taking our chemistry classes but are not chemistry majors. Once again, it is important to note that students who do not own their own devices still may need to have access to chemical drawing software. Ensuring programs like ChemDraw or ChemSketch are available on some campus student computers, and making sure students know these programs are available, can help this minority of students reach out to their professors when they are unable to make it to office hours.

Digital Sketch Software

Another available option that could incorporate both mathematical equations and chemical structures are digital sketch programs. These are widely available applications and software designed primarily for drawing pictures. Technology has far passed the days of the heavily pixilated Microsoft Paint. Students (and professors) have a lot of control of what they are drawing when they use some of the more sensitive applications on touch-screen devices, especially when coupled with the use of a stylus. Using a mouse on a computer can still lead to difficult to interpret, shaky drawings, and, depending on the skill of the user, the same issue can present itself using tablets and smartphones. As seen in Table 3, the lines drawn on these programs can be somewhat disjointed. The user may have to try multiple times to get a reasonable drawing. The best feature of these drawing applications is that it is an extremely fast way to write and send what you write. It takes roughly the same amount of time to draw as with traditional pencil and paper, provided it is legible when drawn the first time. Files are saved and can then be sent directly through email from tablets and smartphones with a few finger swipes. An obvious downfall to these sketch programs is that they are not useful to students who do not own tablets, and for many smartphone users, the screen can be too small to easily draw out their work.

Digital Photography Using Device Cameras

By far, the easiest method for students to communicate mathematic and structure-based chemistry through email is through the use of digital cameras. In addition to regular stand-alone digital cameras, there are also cameras available on nearly every computer, tablet, smartphone, and standard (non-smart) phone, which have the benefit of smaller file sizes than some of the dedicated digital cameras. Their pervasive nature makes them the most accessible method for students to send chemistry questions to their professor. They generally require no extra software, application, or cost. Students can take pictures of their homework or sections of their notes and send the photograph through email for review by their professor. This method has a benefit over the other methods in that students do not need to spend a length of time redrawing their equations and structures (which can have the unintended consequence of reinforcing incorrect information if they have incorrect drawings and equations). Depending on the type of camera, students can send a question in a matter of seconds by taking and sending the picture on the same device. The most problematic issue using this method is that some students take blurry or dark photos that need to be retaken and resent, increasing the time between when they asked the initial question and when they get an answer.

Concluding Points

After experimenting with the above techniques for several years by having students send questions through email, using any method they chose, taking pictures of their work came out as the most practical, most used method. By a large margin, students preferred the photographing method when given all presented options as it was the fastest and required less extra work. However, depending on the issue at hand (lab report question vs. homework question, for example, or not having access to a digital camera), the other presented methods are still useful alternatives. It is important to note that as technology continues to advance, we will continue to find methods of expanding our accessibility for our students in the millennial classroom, and it is important that we keep abreast of the most current trends in technology.

Holding Real-Time Online Office Hours

There is much to be gained in our traditional chemistry courses from learning what new technologies are available for online courses and utilizing them outside of the classroom. There is still a great divide between sending a professor an email and waiting for a response versus getting real-time help for a problem, especially the night before taking a morning exam or turning in a homework assignment. As discussed above, scheduled office hours may not be conducive to the needs of our students who have a demanding work or home schedule. While email is a great resource to use for these students, real-time help can still be available through implementing real-time online office hours. There are a variety of methods available to accomplish this using the tools available from different learning management and web conferencing systems. Additionally, commercial instant messaging services, video communication services, and desktop streaming programs are more accessible methods for reaching students.

Learning Management Systems

Learning management systems were designed to support the unique needs of distance learners and have done a great job in keeping up with new technologies that benefit the students in this way. They have evolved from a repository for course materials and message boards to a fully functional virtual classroom. The most-used systems are Desire 2 Learn (D2L), Blackboard, and Moodle, which currently control 75% of the total market shares (*20*). These systems have similar functions in that they maximize the interactions between students taking online courses and the faculty that teach them. These tend to be user-friendly and have varying levels of accessibility for students with disabilities. Online office hours are available on the most commonly used systems through the use of messaging features and digital whiteboards. Interactions can often be set up between one student and professor, a group of students, or the entire class. An issue with these systems is that they are not as user-friendly for those who do not often use them, students and faculty alike. This can be problematic with students who do not routinely take online classes and would thus have little exposure to these systems. Regardless of device, students would still need to sign-in on the system website to have access, switch to the "desktop version" if they are on a tablet or smartphone, and then navigate the website to get to the messaging features. This is obviously cumbersome for students looking for a quick answer to a relatively simple question. The online whiteboards still have issues with shaky, difficult to interpret sketches and the users typing text are still faced with trying to communicate chemistry structures and equations using a standard alphanumeric keyboard. This is a major shortcoming to using these systems for online office hours with chemistry courses. Additionally, a faculty member may be required to use the system supported by their university, which may or may not have a great interaction interface for the needs of a chemistry course.

Web Conferencing Systems

Web conferencing systems also have great potential for reaching students. Adobe Connect and Blackboard Collaborate are examples that are currently being used by some American universities. These systems allow for an interactive online experience between a professor and all students in the course who are signed into the system. This includes video messaging for people who have a camera, microphones, and speakers, text boxes for those who do not, and an interactive whiteboard that can be used to communicate ideas (*21*, *22*). These systems make online review sessions possible, and students can come in and "meet" with their professor alone or in groups. PDF files can be uploaded into the system for sharing and these systems often have mobile device support. One of the major limitations here is the need to establish which members are allowed access into each conference. While they can be set up for open access where the entire class could be invited, some students desire the privacy of a personalized meeting. In this situation, the professor will need to set up that meeting in the system only available to that student, which requires prior communication and time arrangements. It is not as simple as stopping by during regular office hours but it remains a viable option for students who are unable to meet with a faculty member, or even for a faculty member who is away at a conference, ill, or otherwise physically unavailable to their students. Over the past few years, this method was presented as available for use in the classroom and it was observed that several shy, quiet students who were often absent from classroom discussions and office hours would log in and listen to (or read) the conversation that was happening remotely. These students, who are sometimes inadvertently left behind in class, were able to essentially participate in other students' office hours, and get help through observation without having to leave their comfort zone to be active in the conversation.

Instant Messaging Systems

Instant messaging systems are another great way to hold online office hours. There is evidence that instant messaging services between a student and faculty member are better at helping convey ideas and understanding than through email services, therefore this method holds real promise in helping our millennial students (*23*). Many students use this technology regularly to keep in touch with their friends, and thus, this is a normal, user-friendly, accessible, and free method for communication that students are generally very comfortable using. Some of the more common systems are Skype, Facebook Messenger, and Google Talk. These offer video and/or text messaging capabilities and allow files to be shared either through the messaging platform (Skype and Facebook) or through email (Google). A faculty member can interact with either a single student or a group of students using the available group messaging features. All three systems allow anyone to use them, if the user downloads the free messaging software or application and creates an account. Because the main purpose of these messaging systems is video, photo, and chat communication, students can link them to their digital cameras to provide their professor with easy to understand, real-time questions, and their professor can send them easily understood feedback. All of these systems are great in that only a few clicks with a mouse at a computer, or a few taps on a touchscreen device, can help students get the information they need at a time when they are available while using a platform they are the most comfortable with. For faculty, it helps ensure that they are available for their students when they are needed.

Desktop Streaming Programs

Desktop streaming programs have been around for years but have seen little use in the academic world. These programs allow a professor to stream a video feed of their computer desktop to a channel that students can tune in to, much like a TV channel, through their internet connection. This requires no special software or downloads for the student. Companies like Ustream allow a professor to switch back and forth between standard video chatting, desktop streaming, and a blank screen with optional audio feed for both (or neither) through a free download. Students can send in questions via email, and the professor can have a time set aside for students to tune in and watch as they answer the questions given to them. This allows the streaming and answering of questions through ChemDraw or ChemSketch that all students can see and is coupled with audio feed of a professor explaining the answer to a problem. This has an added benefit of protecting the anonymity of students who are shy and unwilling to ask question in class and/or in person. It can keep them from feeling embarrassed in front of their peers and can be a less intimidating option for getting help from their professor. The drawback of this is the sometimes time-intensive drawing, though for a professor the time required is much less than for a student using the same program. Coupling the technology with one of the digital sketch systems or online whiteboards can also be useful for quickly communicating full answers to questions.

Concluding Points

Of course, real-time online office hours have the same limitations as conventional office hours in that the student and the faculty member both have to be available at the same time. A professor that indicates to his or her students on their syllabus that appointments can be set up for online office hours will find some students that use them infrequently, some frequently, some never, just like conventional office hours. Another issue is that some students are more familiar and comfortable with one system over another. When given the option between the different methods presented here for online office hours, it was found that the vast majority of students preferred text-only Facebook Messaging and Google Talk over other messaging, learning management, or web conferencing options. Having both programs open simultaneously proved reasonable and allowed the students to have the flexibility to work with whichever system they were most familiar with. In many cases, students have constant access to programs that they use often, which increases the level of convenience for them. As programs gain and fall in popularity among college students, professors will need to adapt by moving their help to those new avenues.

Faculty-Initiated Correspondence: Alternatives to Email

Anyone who works at a college or university is familiar with their email inbox being flooded with messages from all over. It can become quite the chore on a busy day to sort out the important messages from the unimportant. Unfortunately, our students are in much of the same boat. Although we may be sending important, class-related emails to our students, they sometimes go unchecked, unanswered, or discarded. Many students have come forth saying they simply do not check their campus email anymore because of all the junk mail they get on any given day. Others do not like the campus email system as much as their personal email, and never bothered to forward the messages from one to the other. Regardless of the reasons they are not checking it, there are many important issues professors address with their students through email, and there are simply too many students not getting those messages. A common mistake is assuming email is the preferred method of communication for students, when in reality most of them are much more likely to use social media and text messaging for the majority of their daily remote social interactions.

Trends in Social Media

There are trends in social media just like anything else, and it is important for professors to keep abreast of these trends so that they can be utilized to enhance student correspondence. For many years, Myspace was the preferred social media giant, which was then replaced by the still-reigning Facebook. These social media sites serve as online communities dedicated to correspondence between the users. As technology has progressed, so has social media. Some commonly used sites now are Twitter, Tumblr, Facebook, Google Plus, LinkedIn, Instagram, Reddit, and Pinterest. As seen in Table 4, these sites serve different functions and as such, certain groups seem more likely to use one over the other. It is now estimated that 84% of adults ages 18-29 use Facebook, roughly 30% use Twitter, and now there are increasing numbers of students using multiple sites to communicate and socialize (*24*). Simply put, if we need to reach our students we need to look where they are likely to be found: social media sites, and in particular, Facebook and Twitter.

Keeping in Touch Using Facebook

As mentioned in the preceding section, Facebook Messenger has a lot of utility as a platform for online office hours, but as discussed here the site itself is a great method for faculty-initiated communication with students. Most students have Facebook accounts and most of those students check the site daily (*24*). They are able to send and receive messages from their portable devices. It is hard to find a school now without a Facebook presence, either as a single page, or multiple groups set up for different parts of a campus. It is the new normal for communication between students and student organizations, and it can become an effective way to communicate between students and their professors. Setting up a group page for students to join allows them to keep up on messages from their professor such as, "Students, check your email tonight" or "Class is cancelled for tomorrow due to illness". Students can use the class group page to look for or advertise study groups without having to send friend requests to the other students in class; this is especially useful when a student may not know the names of their classmates to message them individually. Facebook is not a substitute for email, since some students still use email, but messages sent to students across both will be seen by a broader audience than using email alone. A primary concern with using Facebook in general for this purpose is the problem of mixing a private life with a professional one, as professors would be given access to their students' profiles. Students can upgrade their privacy settings in their profile which remedies the problem, but some users are not willing to take the extra steps needed to ensure their privacy from their professors, and thus, will remain uncomfortable using it in this context.

Keeping in Touch Using Twitter

Another option for simple communication is Twitter. The sole purpose of Twitter is to send short messages (less than 140 characters) to an audience that subscribes to these messages. Approximately one-third of college-aged students use Twitter (*24*). Although it is not used as often as Facebook, Twitter has the benefit of one-sided subscribing. A student could follow messages from a professor, but the professor does not have to follow messages from the student, which provides a certain level of privacy and comfort for the student users. Like Facebook, Twitter is great for short messages that are broad-audience for an entire class. A shortcoming of Twitter is that it cannot be used to share to the same extent that Facebook can, since the messages are limited in size, but it can still be used to share images, links to articles or videos, and other interesting content that a professor would generally email to their class.

Table 4. A summary and comparison of some common social networking sites used by US colleges and college students

	Primary Uses	*Percent Use Ages 18-29*[a]	*Additional Information*
Facebook	Instant messaging Sharing links Sharing photos Sharing videos Group communication	84%	Group messaging Largest user base No size limits Easy privacy settings
Twitter	Short-form messaging Sharing links Sharing photos Sharing videos	31%	Easy privacy settings Simple to navigate Strict size limits
Pinterest	Sharing photos Sharing videos	27%	For visual media only
Instagram	Sharing photos Sharing videos	37%	For visual media only

[a] These figures include all adults 18-29, not just college students.

Text Messaging from Your Campus Email

Text messaging has also evolved a great deal in the past few years and it has reached the point where nearly all students text daily (*19*). It is now possible for professors to send messages from their campus email account to a student's phone as a text message. As seen in Table 5, most of the major cell phone providers have this ability and when used sparingly, students respond positively. Care has to be taken to avoid surplus texts and long texts to avoid overcharges for students with low number text plans. This method has the benefit of being near-instantaneous (provided students keep their phone on them) and delivered directly to nearly all students. Messages sent back come to the professors email and not their personal cell number, so that remains private for the professor. The drawback to this method is having to get information about the student's cell provider, and having to manually enter the numbers into their email recipient list; this is obviously time-intensive and perhaps time-prohibitive depending on the class size. Additionally, some of the smaller providers may not participate in this type of service, so the students who use those providers could not use this type of communication.

Table 5. Common US cell phone carriers that allow text messages to be received when sent as an email (*25*)

Carrier	***Send to 10-Digit Phone Number plus***
Alltel	@message.alltel.com
AT&T	@mmode.com
Boost Mobile	@myboostmobile.com
Cingular	@cingularme.com
Nextel	@messaging.nextel.com
Sprint	@messaging.sprintpcs.com
T-Mobile	@tmomail.net
Verizon	@vtext.com
Virgin Mobile	@vmobl.com
Example:	*For phone number 1-555-225-5555,* *send an email to 5552255555@vtext.com*

Concluding Points

As services continue to cater to certain groups of people, we will continue to see that there are so many methods of communication that it is impossible to reach 100% of students with any one method. We can, however, reach a much higher number of students when we combine methods. An easy way to achieve this is to let students know on a syllabus what methods they can use to "find" you online. Let them know whether you accept Facebook friend requests from students, or that you have a group page for the class on the site. Let them know if you have a Twitter account, and assure them that you will not follow their feed so that they have some level of privacy when they want it. Lastly, if the class size is sufficiently small enough, ask students in class what their preferred method for communication is and use it. While there are some schools with specific guidelines about using campus email for correspondence, Twitter and Facebook messages as simple as "students: check your campus email tonight" are sufficient in getting students the information they need when you need them to get it.

Conclusions

On average, the millennial student is dealing with a heavier workload, more family obligations, and a higher financial burden than in previous generations. A primary need for many of these students is an affordable education with flexibility in scheduling their classes and readily accessible instructors for their courses. The relatively recent surge in portable technology, which students are already using for the majority of their daily social interactions, can be utilized by faculty to create high-quality interactions and feedback for their students. Of particular importance are:

1) Increasing the effectiveness of student-initiated email correspondence to be more "chemistry-friendly" through the use of attached image files,
2) Faculty holding remote office hours and review sessions using a mixture of real-time instant messaging services and/or web conferencing systems and
3) Reaching the biggest audience possible for important faculty-initiated correspondence through a combination of social media outlets, email, and text messaging.

The information here is time-sensitive as technology advances are continuous and online habits fluctuate with popular trends (especially in younger adults). The millennial classroom is a dynamic environment enriched with heretofore unprecedented diversity, and to disregard the unique technological needs of the millennial students could prove a disservice to their overall education and future endeavors. Keeping abreast of technological advances and trends is critical to ensuring that faculty will continue to use relevant, effective technologies to reach their students both inside and outside of the classroom.

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