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Polymers Course for Small Colleges and Universities

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ABSTRACT

This article describes the course design and teaching methodology for a polymer chemistry and applications lecture class specifically aimed at small college and university instruction. This intermediate course for advanced undergraduates and masters level graduate students focuses on teaching the basics of polymer history, synthesis and characterization with connections to the core chemistry curriculum in a small class size environment and without a textbook. Furthermore, an extensive overview of the applications of polymeric materials gives students a connection to real life applications. The course includes polymer case studies, informational lessons on real world objects made of polymers, and demonstrations. Student presentations on how polymers are important to society help connect the course to the world around them. The course is designed to instill the knowledge necessary for students to be successful in a career in polymers. A brief discussion of course reflections and student input is also given.

INTRODUCTION

Polymer science is typically under-represented in small colleges or universities chemistry curricula even though about half of all chemists will work in this field at some point in their careers; especially those colleges with lesser emphasis on research programs (*https://www.acs.org/content/acs/en/careers/college-to-career/chemistry-careers/polymers.html*). One of the major limitations to adding instruction in polymer education dating back to at least the

1950's is that colleges traditionally stick to the core disciplines of chemistry including organic, inorganic, analytical, physical and biochemistry for hiring, course purposes, and degree requirements even if the professors have PhD and/or Post Doctoral training in other areas including polymers/macromolecules. Even if some of them had been exposed to polymeric materials in their graduate studies, there leaves no motivation to revamp decades' worth of curriculum, to expand outside their comfort zone and to incorporate polymer course materials into the current course load or to add dedicated courses. (Kice, 1959; Billmeyer, 1959; Jefferson & Phillips, 1999; Stenzel & Barner-Kowollik, 2006). Furthermore polymer education was not part of many certified/accredited degree programs, including the American Chemical Society Certified Degree program, leaving no motivation for schools to advance curriculum in this area; however this is finally changing with the most recent requirements for the ACS Certified Degree requiring macromolecule/polymer education (https://www.acs.org/content/acs/en/about/governance/committees/training/acs-guidelines-supplements.html).

Over the years a series of efforts have attempted to integrate polymer topics within the core subject areas of chemistry, most notably as reported by the polymer core course committee during the 1980's, which discuss the addition of polymer topics to each core area (Core course committee in general chemistry, 1983; Miller et al., 1984; Howell, 2013; Core course committee in physical chemistry, 1984; Droske, 1995) Recently there has been an effort to stress the teaching of polymer science, and many guidelines have been proposed, however mostly to deaf ears, likely leaving graduates underqualified and underpaid for today's job market (Seymour, 1982; Jefferson & Phillips, 1999; Hamaide, Holl, Fontaine, Six, & Soldera, 2012; Goh, 2013; Carraher & Deanin, 1980; Mahaffy, 2004; Cavalli, Hamerton, & Lygo-Baker, 2015) The new degree requirements, which include instruction in macromolecules/polymers leave smaller institutions with a challenge as to how they can meet these new stipulations. These institutions are not likely to have the resources to hire a dedicated instructor for teaching polymers and must find creative ways to incorporate instruction into their current courses or implement something that can be taught by the current faculty. In order to overcome some of the limitations presented for current faculty, a number of polymer-teaching workshops and free online courses have been implemented at universities to impart the necessary knowledge needed to include a connection to polymers in professors' courses (Stinson, 1989; http://www.open.edu/openlearn/science-maths-technology/science/chemistry/introduction-polymers/content-section-0?active-tab=description-tab) Some small universities may also be able to hire qualified adjunct professors to teach such classes.

There have been a few education articles over the years that have suggested various course topics and training methods for polymer chemistry (Seymour, 1982; Jefferson & Phillips, 1999; Hamaide et al., 2012; Goh, 2013; Carraher & Deanin, 1980; Mahaffy, 2004; Cavalli et al., 2015). This article will describe the design and teaching methodology of a polymer chemistry course for advanced undergraduates and masters-level graduate students at small primarily undergraduate institutions (PUI), a course that could be taught by any savvy chemistry professor outside of polymers, an instructor with a background in polymer chemistry, or a knowledgeable adjunct. This course is perfect for small colleges and universities as it gives students a broad survey of synthetic techniques, correlations to core chemistry subjects, and a review of everyday applications in polymer science.

COURSE DESIGN

The goals of this course are to give students a broad understanding of the principles of polymer chemistry and applications at an intermediate level with little starting knowledge of what polymers are. This includes developing a basic knowledge of polymer synthetic techniques, characterization, and topics on the many applications of polymeric materials and their connection to other disciplines of chemistry. In detail these goals include developing a global perspective of interdisciplinary issues involved in polymers; learning how to design, synthesize, evaluate, analyze, and implement functional polymeric materials; critical thinking and analysis skills to develop research interests and proposals; and finally, effective communication of ideas both individually and within a group through written and oral communication (Porter, 2007).

This class was designed to use Internet and library resources instead of relying on a single purchased course textbook, which kept costs lower for students (See SI for instructional materials links). As an instructor however, textbooks are a useful basis for starting preparation for the course. A few good textbooks and online resources such as the MIT open courseware page are useful for instructors putting together courses and are given in the SI.

Students are encouraged to look up references and presentation topics given in class using primary literature including pubs.acs.org and sciencedirect.com (both resources available at many smaller institutions). Industrial and government trade magazines such as Tech Briefs, Chemistry World and C&EN were used to find exciting new applications of polymers, and for students to design their in-class presentations. Other resources such as the Michigan State University Polymer Page (https://www2.chemistry.msu.edu/faculty/reusch/VirtTxtJml/polymers.htm) UCDavis ChemWiki, (http://chem.libretexts.org) and the book Polymers: Chemistry and Physics of Modern Materials were also used to reinforce student knowledge and develop lecture material (Cowie & Arrighi, 2008).

The course is split into two parts, which are roughly half a semester each (equivalent to 150 instructional minutes per week in a 15 week semester). The first part of the course goes through the basics of polymer chemistry including a brief history and discussion of Nobel prizes (Stahl, 1981), synthesis and characterization, while the second half is mainly focused on the applications of interesting functional polymers (Table 1). Though the course is taught as a combination synthesis and applications, the two parts could easily be split into two separate courses covering in depth knowledge of each topic area. Both parts are covered in this course to keep students excited for what "cool" applications were to come.

Table 1. Sample course outline showing topics and presentation schedule for a short semester two day a week polymer chemistry course taught at the University of Detroit Mercy. The info lessons (real life connections) and case studies were performed by the instructor, and presentations were done by students).

Lecture	Topics	Presentations
1	- Orientation and Polymers Introduction	Info Lesson
2	- Organic Polymerization Methods: Synthesis and Properties	
3	- Organic Polymerization Methods Cont./Block Segmented Copolymers	Case Study
4	- Conjugated Polymers: Photonic and Electronic Properties and Applications	Short 5min
5	- Dynamic Covalent Polymers/Organic Frameworks	Short 5min
6	- Hybrid Materials: silicones, silsesquioxanes and other inorganic polymers	Short 5min
7	- Midterm Exam (Lectures 1-6)	
8	- Polymer Solar Cells, Nanomaterials, and Self-assembly	Info Lesson
9	- Polymer Actuators/ Gels and Smart polymers	
10	- High Performance Polymers	Case Study
11	- Biodegradable Polymers/ Non-fouling Materials/ Biomimetics	Long 25 min
12	- Biosensors	Long 25 min
13	- Polymers for Drug Delivery and Tissue Engineering	Long 25 min
14	- Final Exam (Lectures 7-13)	

The course covers a wide range of topics including general polymerization techniques of basic polymer systems (i.e. polystyrene, nylon-6,6 etc), block copolymers (structural motifs, types of blocks), conjugated polymers and their photonic and electronic properties and applications, high performance polymers (smart polymers, actuators, gels), hybrid polymers (silicones, silsesquioxanes and other inorganic polymers) and biopolymers (drug delivery, tissue engineering, biodegradable, non-fouling and biomimetics). The synthesis, properties, and the industrial, biomedical and optoelectronic applications of all of these materials are discussed. Students learn design principles to achieve specific functions from polymers, synthetic methodology, structure-property relationships, and fabrication of devices from polymers.

The course is designed as an introduction to polymer chemistry with a minimum requirement of undergraduate organic chemistry being completed so some topics such as kinetics and thermodynamics were only discussed in their simplest of terms, but depending on the level of your students, a more in-depth study may be appropriate. The polymerization reactions discussed are broken down as simply as possible to fundamental organic chemistry with each mechanistic step being shown in detail. This made the class move at a slower pace to ensure suitable understanding, so that students could retain this information after course completion, and use it throughout their careers, something more important than covering every subject in extreme detail in an introductory class, even without a laboratory component. Though a laboratory course in polymer chemistry is not presented here, it can be very beneficial to aid in gaining hands on experience with many of the techniques (http://www.pslc.ws/macrog/lab/), but is likely resource limited at many schools. It is recommended for simplicity to include a polymerization experiment into the organic chemistry lab without the need for a full course; as an example, Matyjaszewski and others have designed simple procedures such as for controlled radical polymerization experiments (Beers, Woodworth, & Matyjaszewski, 2001; Wackerly & Dunne, 2017; Tsarevsky, Woodruff, & Wisian-Neilson, 2016).

If an instructor is interested in tying some aspects of this course into an organic chemistry course some parallels can be made (Goh, 2013; Schaller, 2017). As an example condensation reactions are discussed in great detail in organic chemistry courses. Many polymers (i.e. epoxies, polyesters) are formed by condensation reactions as well. These could be easily integrated into those lesson plans and discussed as doing the same condensation reaction repeatedly to make a long chain.

TEACHING METHODOLOGY

Teaching is conducted through a variety of methods and is adjusted depending on the type of material being presented. Polymer synthesis methods are taught by board lecture, real life examples, class discussion and interactive case studies. This is a slower approach, but it often helps students solidify knowledge, have time to prepare to ask questions and better discussions. This slower pace method is especially important for students with very little or no exposure to polymers, and many of whom have no experience with radical initiated reactions and mechanisms. This method also allows for drawing clear connections with organic chemistry.

For the application part of the class, lectures are taught using a mix of computer aided presentations and videos from scientific research publications (Kraft, Rankin, & Arrighi, 2012). These were supplemented by pointing out important points and connections on the board to solidify concepts. The presentation videos allowed for showing the complexities and awe-inspiring nature of modern materials in a way unattainable through drawing. Most of the applications portion of the course is put together using primary literature from journals such as Macromolecules, Polymer Chemistry, Chemical Communications, JACS, Nature, and Science, etc. This allows for some of the newest and most exciting topics in polymer science to be presented and connected to the synthesis techniques examined in the first part of the course. The biggest challenges with using primary literature is that many of the articles are very advanced to upper level undergraduate or first year masters students, so great care must be given to clarify and connect the advanced concepts back to the basic polymer chemistry learned in the first part of the class.

The lectures are broken up by a series of class and/or group activities. The first type of activity is a case study discussion (Campbell, Powers, & Zheng, 2015). This is most often a recent paper using a polymerization method discussed in class. The problem is presented with background, and split by either showing how the researchers solved the problem or gave the problem without a solution, in both cases using their learned knowledge to see what kind of method they could come up with. As an example, students are presented with a problem related to polymer membranes in proton exchange devices. The device structure of a proton exchange device is discussed as well as limitations with current technology. The standard polymer Nafion® is introduced and its potential limitations were determined through class discussion. A potential replacement is then introduced from using phosphonic acid block co-polymers made by anionic polymerization (Perrin, Elomaa, & Jannasch, 2009). A learning example is introduced showing the importance of structure in anionic polymerization, with unsterically hindered monomers undergoing nucleophilic substitution at the phosphonate instead of undergoing anionic polymerization. By adding steric bulk to the initiating monomer, polymerization proceeded. The differences in properties between Nafion® and this new material are then compared and contrasted.

The second activity is the discussion of real life applications of polymers examined in class. The C&EN series What's That Stuff? and Tech Briefs are both useful in designing short info lessons (<5 min) about objects familiar to the students (https://cen.acs.org/collections/wts.html; https://www.techbriefs.com). For example, the history and materials evolution of golf balls over the years are discussed, with students being highly interested in these subjects and realizing that polymers are everywhere (Gorss, 2005). Something they never really connected before.

Demonstrations are also done during class, which is important exposure given the limited ability PUI's have in offering polymer chemistry in a lab setting (Rodriguez, Mathias, Kroschwitz, & Carraher, 1978). These demonstrations were hands on and in a small course of <10 students. Many may be done as mini labs with each student doing their own experiment, such as the simple Borax and Elmers glue "putty" experiment (https://www.stevespanglerscience.com/lab/experiments/glue-borax-gak/). Demonstrations include showing the students the synthesis and then discussion of the chemistry taking place. Examples include synthesis of nylon-6,6, a two-part epoxy resin, a series of silicone elastomers and the multiple polymer makeup of a golf ball core. Seeing the chemistry happen in front of them really helped the students make connections between the structures they saw and the physical material that resulted, helping to alleviate the lack of a dedicated lab component through active classroom learning.

STUDENT REQUIREMENTS

Throughout the course, students are required to take two exams, one on synthesis and characterization, and one on polymer applications; or one for each part of the course worth 30% apiece (Table 2). Each exam is written to be ~2h long and has a mix of short answer, diagram drawing, mechanism, multiple choice and true and false questions (see SI). A distribution of question types is used to help students maximize and gauge their understanding. Students are given ungraded practice questions before the exams with a list of potential topics and had the opportunity to go through the questions during class and at office hours. Typically a 10% curve has been needed to adjust course grades for the exams, as the critical thinking and analysis questions are written to be challenging.

Table 2. Course requirements and grading.

Requirement	Grade (%)
5 min Presentation on a polymer topic important to society	10
Exam 1	30
25 min Presentation on research and teaching topics in polymer science	25
Exam 2	30
Attendance	5

Students also give two presentations throughout the course (see SI for rubrics). The first presentation (worth 10%) is only 5 minutes in length and is on a polymeric materials topic and how and why it was important to society (i.e. water purification membranes). Students are graded on their ability to stay within the time requirements, that the topic is important to society, their understanding of the topic, ability to answer questions and also their presentation formatting. The second presentation (worth 25%) is a 25 min expansion of a topic discussed in class or the teaching of a specific technique in polymers not examined in lecture (most students choose the former). The class is encouraged to explore the primary journal literature to find appropriate topics (i.e. organic solar cells). Students are graded heavily on their understanding of the topic they are presenting, adequate referencing, and that their conclusions were appropriate and thoughtful. Detailed rubrics for each presentation type are given to the students at least 2 weeks prior to their scheduled presentation date.

Attendance is also added as 5% of the grade to entice student participation, mainly because this particular course is taught as a special topics short semester evening course for masters-level students and missing one class put them a week behind. As a note, graded homework was not given in this course, but is a viable option to solidify polymer problem solving skills, and a group project was not proposed in the course syllabus due to the commuting distance of many of the graduate students and many worked during the day.

REFLECTIONS AND STUDENT VIEWS

Courses like this taught at Primarily Undergraduate Institutions (PUI) will likely have few students, making them malleable with strong instructor-student interactions and constant feedback. This also means adjustments to the course material, syllabus and course pace are more easily implemented. Students are regularly asked throughout the course what they think of different aspects of the teaching style and topics so that the course can be tailored to maximize interest and understanding. One of the major challenges to teaching the course was that ~75% of the students spoke English as a second language, and often had a difficult time understanding topics. To tailor to this, many topics had to be slowed down, with many questions answered during class, and with further reinforcement given during office hours.

One of the major advantages to splitting the course into two parts, polymer chemistry and applications is that students are interested in different aspects. Half the class enjoyed the polymer chemistry part more, while the other half of the class preferred the applications section. In the course evaluations students expressed how much they loved the class and wished they had been given the opportunity earlier in their careers (before graduate school) for such a class and highly recommended it to future students.

To start the implementation process of a course in polymer chemistry at a small institution it is smart to run the class in trial form as a special topics course so that some student course outcome and review data can be compiled to help aid the discussion with the administration. Other important ammunition is included in the ACS Certified Degree program, in which macromolecular/polymer education is now required to stay compliant and must at least be a component of traditional courses for a certified degree (https://www.acs.org/content/acs/en/about/governance/committees/training/acs-guidelines-supplements.html).

CONCLUSIONS

In conclusion, the development ideology and teaching methods of a polymer chemistry and applications course suitable for small colleges and universities has been discussed. The approaches described would allow instructors with little or no experience in polymer chemistry to develop their own courses, and/or incorporate polymer topics into their core courses. Polymers will continue to be an important part of everyday life for many years to come (Ritter, 2002) and therefore education about their syntheses, function, and properties will only become more important.

SUPPORTING INFORMATION

The supporting information includes additional resources for course material, demonstrations, rubrics for presentations and example exam questions.

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