Chemical Nanotechnology: A Liberal Arts Approach to a Basic Course in Emerging Interdisciplinary Science and Technology

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The extraordinary idea of functional devices and structures 1,000–100,000 times smaller than the width of a single human hair excites the imagination and fears of scientists, engineers, the media, politicians, science fiction authors, Hollywood, and the general public. The study and manipulation of matter on the nanometer scale (measured in one-billionths of a meter) has been termed nanoscience or nanotechnology, an exploding field still in its infancy *(1, 2).* Unique, unpredictable, and highly intriguing physical, chemical, optical, and electrical phenomena can result from the confinement of matter to nanoscale features. As a result, the promise of amazing discoveries relating to the study and preparation of structures exhibiting such interesting and unusual phenomena has attracted the focus of scientists and engineers from across the globe. Much of the driving force for building infinitesimal devices and features on the nanoscale derives from their importance for existing and emerging technologies. These include micro- or nanoelectronics, sensors, molecular computing, and medical diagnostics, among others *(2).*

Over the past few years, the notion of nanotechnology has escaped laboratories and disseminated into popular culture. Check the newspaper, surf the Internet, or look to recent sci-fi books and movies, because nanotechnology seems to be everywhere these days. In response, a new course was developed *(3)* to serve undergraduate students, regardless of major, who have completed one semester of introductory chemistry coursework. This course focuses on the fundamental science behind the major research initiatives of the field, science fiction, and the media hype. The emergent notoriety of nanotechnology provides an exceptional opportunity to highlight the amazing opportunities that arise when various disciplines of science interact. The course revisits the origins of the field and spotlights current advances. Students are also challenged to consider the political, economical, environmental, and ethical concerns relating to nanotechnology and its potential impact on modern society. In addition to lecture and guided discussion, students participate in writing, molecular modeling, and laboratory exercises. Utilization of a central text is supplemented by examples taken from the primary chemical literature as well as selected works of science fiction.

Objectives

Nanotechnology is one of the largest and most rapidly growing interdisciplinary research fields in modern science and engineering. Research institutes dedicated to the area continue to be founded worldwide, while federal funding initiatives sustain this burgeoning field. Thousands of articles are published every year in the field with new titles emerging in both print and virtual formats. While many of its proponents foresee nanotechnology ushering in the next industrial revolution *(1, 4),* the field is principally in the early stages of developing the tools and methods for manipulating and characterizing structures on the nanoscale. A relatively small, yet growing, number of graduate level and undergraduate courses have focused on this enticing subject.

While the potential impact of the field is acknowledged, this course seeks to spotlight the interdisciplinary nature of nanoscience and nanotechnology. Although dedicated nanotechnology degree programs have recently been initiated at various institutions *(5),* the sustenance of such interdisciplinary efforts relies upon the contributions and collaborations of talented individuals across many disciplines. Nanotechnology provides an excellent way of learning to look at the amazing opportunities that arise when various fields of science and engineering converge. Therefore, as educators, we can utilize this as an opportunity for applying and reinforcing the fundamentals students learn in subdisciplinary courses to applications and problems with a broader scope. Students sometimes fall victim to the “tunnel vision” that may result from a rigorous, specialized curriculum and fail to appreciate the coursework of their major in context *(6).* Furthermore, gaining an appreciation of other viewpoints may prepare students to become innovative chemists, biologists, physicists, and mathematicians by serving to provide them insights in attacking more traditional problems in the field through novel approaches. Nanotechnology allows for a true liberal arts approach to an exciting interdisciplinary area of science and engineering.

Although reinforcing the fundamental science curriculum is a major goal of this new course, the liberal arts approach also demands that the interaction of science in the context of larger societal issues be emphasized. Now, more than ever, the feverish pace by which technology evolves and enters our consumer markets directly influences popular culture and has the potential to transform our society. Nanotechnology has increasingly garnered the focus of authors, news outlets, movies, and television, and some that might unethically exploit the popularity of the subject for financial gain. Therefore, a serious commitment was made to identify and combat the variety of misconceptions surrounding the subject. Furthermore, a sincere effort was made to guide our students, as educated citizens, toward the consideration of the social, political, economical, environmental, and ethical issues related to a technology with such potential impact.

Classroom and Internet Resources

Selection of a central text was a major challenge facing the development of this course owing to the fact that undergraduate-level nanotechnology texts are scarce. Although there is no shortage of books published on the subject, most are either highly technical reference works aimed at graduate students and researchers in the field or those that forego the science and present a glamorous depiction of the future impact of nanotechnology. We felt that the adoption of a central text that bridged the gap between these traditional categories was crucial to the success of this course. For this reason, we ultimately elected to adopt *Nanotechnology: Basic Science and Emerging Technologies,* a text recently published by CRC Press *(7).* The book successfully introduces the field, reviews the prerequisite introductory chemistry concepts, spotlights various research areas, and finally considers some of the social implications of nanotechnology. Futhermore, the text frequently does an excellent job of breaking down the acronyms and idiosyncratic vocabulary that permeate the field, relating them to more fundamental concepts. Molecular self-assembly, for example, is rationalized in terms of intermolecular forces and basic thermodynamic arguments familiar to the general chemistry student. In addition to the central text, reading assignments from *Scientific American* provided introductions and reviews of major nanotechnology research initiatives *(8).* As previously mentioned, a variety of current articles from the American Chemical Society journal, *Nano Letters,* were utilized to introduce students to the primary literature and demonstrate that concepts were dynamic in nature and that the body of knowledge is continually growing.

As a supplement to the science and research focus, the classic Drexler text, *Engines of Creation*, was assigned and discussed for its predominant role in the popularization of the subject *(4).* Furthermore, the Drexler text provided a convenient vehicle for transitioning classroom discussion from fundamental science to focus on the potential impact of nanotechnology on society, ethical concerns, and the possible environmental consequences of nanotechnology. Similarly, Michael Crichton's *Prey (9)* and other works of science fiction helped highlight many of these social issues and popular perceptions of nanotechnology. Two nanotechnology science fiction anthologies in particular, *Nanodreams (10)* and *Nanotech (11),* served as resources from which a diverse collection of fiction was obtained for classroom use. For example, Greg Baer's "Blood Music" *(10, 11),* one of the first science fiction short stories to specifically relate to nanotechnology, and Kevin Anderson's "Dogged Persistence" *(10)* were utilized in motivating classroom discussions. Finally, video clips from several popular science fiction movies and television series served to stimulate discussion relating to popular fears and misconceptions surrounding nanotechnology *(12).*

In addition to these readings and lecture handouts, many computer software and Internet resources were employed. Molecular modeling using the PC Spartan Pro software suite *(13)* is integrated into every level of the chemistry curriculum at this College *(14).*[1] Utilizing their familiarity with the software, students were challenged to model and perform simple calculations for fullerenes, carbon nanotubes, rotaxanes, catenanes, and quantum dot structures. Blackboard *(15)* proved to be an invaluable tool in serving as the central nexus for course information, announcements, Internet links to recent news articles relating to nanotechnology, the primary chemical literature, and other relevant Web resources such as the National Nanotechnology Initiative (NNI) Web site *(1).* Moreover, the Blackboard software allowed students to participate in online discussions, view their grades, retrieve color copies of the lecture handouts, obtain duplicate copies of supplemental readings, problem sets, or laboratory handouts, and quickly communicate with the instructor or fellow students via email.

Course Structure and Content

As a departure from the traditional fourth-year special-topics courses, any student having completed one semester of introductory chemistry was invited to enroll in the chemical nanotechnology course. In keeping with the objectives of the course, students from various majors and classes were encouraged to participate. Enrollment consisted of four first-year, four third-year, and two fourth-year students of various majors, ranging from biology to religion. The initial course meeting consisted of a brief introduction and viewing of "The New Breed", an episode of *The Outer Limits* television series *(16),* which served to spotlight many of the popular fears and misconceptions of nanotechnology. This was followed by a guided class discussion regarding the students' preconceived notions of the subject, which was continued after class utilizing the Blackboard online discussion option. Aside from the initial class, semiweekly course meetings consisted of ~40 minutes of lecture and ~35 minutes of guided discussion focusing on an assigned reading or questions stemming from lecture topics (Table 1). Course material was selectively partitioned and presented as a series of four course modules commensurate with the objectives of the course.

Module I: An Introduction to Nanotechnology

The initial course meeting introduced course policies and grading, a general overview of course objectives, and concentrated on developing working definitions of both nanoscience and nanotechnology. Students completed a brief nanotechnology questionnaire (see the Supplemental Material[W]) to glean valuable insight into their preconceived notions of the field. A brief historical timeline of nanotechnology was presented, and by revisiting the origins of the field, students were shown that nanotechnology has been studied for some time under the classifications of condensed matter physics, surface science, and materials engineering, among others. Richard Feynman's seminal lectures *(17)* were briefly explored and served to reinforce the fact that the enthusiasm for examining the minuscule is nothing new. Finally, the class viewed the aforementioned *Outer Limits* episode and the following discussion served as a wonderful icebreaker for the students. More importantly, the discussion served to illuminate many of the common misconceptions of nanotechnology shared by the students.

Module II: Viewing the Nanoworld

Nanotechnology research results are habitually presented in an exceedingly visual manner, frequently displaying a myriad of electron or scanning probe micrographs *(2)*. In presenting the historical timeline of nanotechnology, a conscious effort was made to spotlight the development of the electron microscope and scanning probe microscope. The second course meeting elucidated the instrumentation central to the characterization and manipulation of nanoscale materials. The

Table 1. Course Outline

Course Meeting	Topics Considered (L = Lecture, D = Discussion)	Assigned Readings
1	L: Brief History of Nanoscience and Nanotechnology D: *The Outer Limits*, “The New Breed”	Syllabus and Course Information
2	L: Nanostructures by Inference: Tools of the Trade D: Drexler and Feynman	Stix article (8); Drexler, chapters 1–3; Wilson, sections 1.1–2.7, 2.9, 2.10
3	L: Molecular Self-Assembly I: Order from Chaos? D: National Nanotechnology Initiative (NNI)	Andrews NNI account *(10)*; Wilson, sections 2.11, 6.3, 2.12
4	L: Molecular Self-Assembly II: Nature Shows the Way D: Nanofabrication	Whitesides–Love article *(8)*; Drexler, chapters 4–5; Wilson, sections 6.1–6.8
5	L: Molecular Machines: Synthetic Mimics D: Michael Crichton’s *Prey*	Crichton, pp 1–139; Astumian article *(8)*; Wilson, sections 5.1–5.15
6	L: Nanoparticle Materials: Colloids Reborn D: Smalley–Drexler Debate	Drexler, chapters 6,10; Wilson, sections 3.1–3.11
7	Laboratory Exercise #1 Preparation of Magnetic Nanoparticles	Lab #1 Handout
8	Review and Exam #1	
9	L: Nanoelectronics: Pushing Moore’s Law D: Chips of the Future	Reed–Tour and Lieber articles *(8)*; Wilson, sections 8.1–8.10
10	L: Group IV (C,Si,Ge): Buckyballs, Nanotubes, and Nanowires D: Nanomedicine	Alivisatos article *(8)*; Drexler, chapters 7–9; Wilson, sections 4.1–4.9
11	L: Future Directions and Hopes (NanoDreams) D: Michael Crichton’s *Prey*	Crichton, pp 139–335; Wilson, sections 9.1–9.11
12	L: Nanotechnology Dangers (NanoNightmares) D: Hopes and Consequences of Nanotech	"Blood Music" *(10,11)* and "Dogged Persistence" *(10)*; Drexler, chapters 11–12; Wilson, sections 10.1–10.9
13	Review and Exam #2	
14	Laboratory Exercise #2: Preparation of Metallic Nanoparticles	Lab #2 Handout
15	L: Ethics & Misconceptions of Nanotechnology D: Michael Crichton’s *Prey*	Crichton, pp 335–502; Drexler, chapters 13–15

NOTE: This is a half-semester course.

fundamental limitations of traditional light microscopy were explained and naturally transitioned into a discussion of the basic principles of electron microscopy. Scanning probe microscopy was considered for its role as both a characterization and fabrication tool. Instrument design and operation were explored for both techniques. Special emphasis was placed on the morphological and topological data obtained from the respective techniques. For emphasis, the importance of these characterization tools was demonstrated in the presentation of various prominent examples taken from the primary literature.

Module III: The Science Behind the Hype

The principal module of the course, consisting of six class meetings, strove to illuminate the fundamental science behind many of the key concepts and focus areas of nanotechnology. An introduction to the National Nanotechnology Initiative (NNI) served to highlight the major interdisciplinary research initiatives in the field *(1)*. Classroom discussion of the NNI revealed and emphasized the significant contributions of chemistry, biology, physics, and mathematics to each of the major research endeavors. Students were encouraged to consistently identify and explain the inventive ways in which the fundamentals learned in introductory science courses are applied to applications and problems in the field. Keeping with the objectives of the course, this approach was maintained throughout the duration of this module. Next, the science of nanofabrication was explored. Intermolecular forces, introductory thermodynamics, and examples from biology, such as DNA and lipid bilayers, were utilized to explain and emphasize the importance of molecular self assembly in the preparation of self-assembled monolayers (SAMs), among others *(5)*. Nanofabrication methods (e.g., dip-pen nanolithography, microcontact printing, etc.), molecular machines, nanoparticle materials, conventional and molecular electronics, fullerenes, carbon nanotubes, and semiconductor nanowires were explored utilizing an analogous approach, spotlighting the fundamental science behind the nanotechnology. The module was concluded by a gradual transition to focus on the potential applications of these materials and techniques in nano-medicine and future generations of micro- or nanoelectronics and micro- or nanoelectromechanical systems (M/NEMS). The recent Smalley–Drexler debate served to highlight the fact that the field is rapidly evolving and that viewpoints, even among proponents of the field, are quite diverse *(18)*. Finally, in an effort to provide a direct link to the implementation of these applications, an alumnus working toward the commercialization of nanotechnology provided an insightful guest lecture for the students *(19, 20)*.

Module IV: Exploring Nanodreams and Nightmares

These course meetings, toward the end of the half-semester, transitioned the course focus toward the consideration of the political, economical, environmental, and ethical issues related to a technology with such potential social impact. The course first focused upon the potential benefits derived from future developments in nanotechnology. Lecture and classroom discussion explored possible applications in new modes of drug delivery, medical diagnostics, alternate energy sources, environmental remediation and sensing, space exploration, microelectronics, national defense, and artificial intelligence, among others. The implications of these advances with respect to a changing U.S. and world economy, current world dependence on fossil fuels, ecological impact, health care costs, national defense, consumer electronics, and overall quality of life were considered. Students also reviewed the political history of the NNI, its fiscal budget, and evaluated the implications of legislation such as the 21st century Nanotechnology Research and Development Act, passed by Congress and signed by President Bush in December 2003 *(1).* Nanotechnology, while offering the hope of dramatically improving many aspects of our daily lives, also poses some inherent dangers. These dangers, both real and imagined, were topics of guided student discussion. Overproduction of inexpensive products leading to massive environmental damage; the proliferation of low-cost surveillance and weapons systems leading to a new type of arms race; the possible adverse health effects related to nanoparticle-base products; the infamous “gray goo” *(5)*; and consequences of pervasive, renegade replicators were a few of the possibilities examined by the students. Several works of science fiction were especially helpful in bringing many of these issues to light and stimulating student discussion *(19–12).* However, to demonstrate that not all of the dangers lie exclusively with the technology, students investigated the ethical misjudgments surrounding the Jan Henrik Schön molecular electronics controversy and its impact on this emerging field *(21).* Finally, in the concluding course meeting, students were encouraged to reflect on how prevalent misconceptions of nanotechnology are represented in television, motion pictures, and in some product advertisements. Students were then required to reflect on how their preconceived notions of nanotechnology had been challenged throughout the course.

Quizzes, Problem Sets, and Exams

In addition to lecture and discussion, daily reading quizzes were conducted during the first ten minutes of random class meetings (see the Supplemental Material[W]). These brief exercises were critical in identifying student misconceptions and were aimed at helping students in determining the main concepts portrayed in the assigned readings. Similarly, BAT (Be Able To) learning objective lists accompanied most reading assignments (see the Supplemental Material[W]). Four homework problem sets were distributed over the duration of the half-semester, each to be completed by the students in a period of one week. The problem sets contained an assortment of molecular modeling exercises, instrumentation understanding, scientist and concept identification, and basic questions accompanying an article from the primary literature (see the Supplemental Material[W]). Critical reading skills with respect to primary literature sources are essential in the pursuit of any area of study *(22).* This initiative was reflected in the exam structure for the course. Each of the two course exams consisted of two, separate sections (see the Supplemental Material[W]). The first section, which was completed in class by the students, contained a variety of conceptual and identification questions central to the material discussed in class or emphasized in the assigned readings. The second section consisted of a limited number of questions regarding an attached primary literature article, to be completed and submitted before the subsequent class meeting. This take home portion removed much of the anxiety associated with typical in-class test taking by allowing them more time to carefully read and analyze the article of interest.

Lab Exercises

As a complement to lectures and readings, students participated in two brief laboratory exercises: the preparation of citrate-stabilized gold nanoparticles and preparation of an aqueous ferrofluid *(23).* Each was completed in place of a regular class meeting, so that scheduling external course meeting times was unnecessary. A formal laboratory report was required for each exercise. To introduce modern journal article preparation and submission, students were required to prepare a two page, two-column report, formatted as a *Journal of the American Chemical Society* communication. Students were required to download and employ the class laboratory report template from the Blackboard course Web site and were allowed to submit their reports in either print or electronic format.

In a concerted effort to introduce a significant writing component into the course *(24),* a final paper assignment was given in place of a final exam. Students were allowed the choice of preparing a quality work of science fiction, crafted upon the concepts and issues discussed in class, or a research paper focused on exploring an area of nanotechnology research in more depth. While a few chose to research topics that caught their attention, the majority opted to compose their own work of science fiction, employing their new understanding of nanotechnology. Topics and preliminary outlines were submitted for approval and the instructor served as a willing consultant throughout the writing process. At the conclusion of the course, the student reports and short stories were compiled into an in-house publication format. The final course grade for each student was assigned on the basis of cumulative discussion contributions (15%), two exams (30%), four problem sets (15%), seven reading quizzes (10%), two laboratory reports (10%), and the final paper (20%).

Evaluation and Future Directions

Course evaluations and casual feedback indicated that the students enjoyed the course and voiced a variety of motivations for deciding to enroll in the course. Some of the more prevalent reasons included students’ exposure to nanotechnology as portrayed in popular movies and publicity produced by media outlets or desires to pursue graduate research in the field. Interest in discovering the possible medical applications of nanotechnology due to medical school ambitions and curiosity surrounding the current state of nanotechnology research were also noted by the students. Additionally, it was significant to observe that the current generation of students is inherently quite tech “savvy” and many enrolled in the course to stay abreast of the revolutionary innovations driving the development of future generations of microelectronics and related consumer products.

Regardless of the motivation behind enrollment, students were enthusiastic, actively engaged in the subject matter, and performed well. The first-year students in the course noted that they felt challenged in applying their general chemistry knowledge to nanotechnology concepts, but were not beleaguered by the course, while the fourth-year students discovered that the course spotlighted relevant applications of the fundamentals that had become a bit distant over the years. Most importantly, students appreciated the direct link between their fundamental science and mathematics courses and the myriad of cutting-edge research initiatives and applications discussed in class. Medical applications of nanotechnology, micro- or nanofabrication of electronics, and molecular self-assembly were indicated as the most popular topics by the students. Furthermore, students were excited by their exposure, the first for many, to the primary literature and expressed that these sources greatly enhanced their classroom experience in emphasizing the contemporary nature of the course material. The two laboratory exercises were enjoyed by the students, who expressed that a more involved laboratory component would greatly enrich future versions of the course. The final paper assignment was the most popular assignment with the class, who appreciated the freedom to select their topic. The quality of both the short stories and research papers was outstanding. Chief criteria in judging short-story quality consisted of peer evaluations, significant use of nanoscience as a central plot device, portrayal of the interaction of science and society, originality, and overall quality of writing. Short-story topics spanned the gambit from utopian visions of the colonization of Mars to the dark, malevolent nightmares of infectious nanobots and mankind's propensity for destruction, while research papers focused on topics such as quantum dot structures and nanomedicine.

Without exception, the students agreed that the course had drastically altered their perceptions of nanotechnology. Many had entered the course with visions of nanobots and gray goo, yet departed with a much more sophisticated view of the subject matter. Examples of student comments to this included, "I came into this course thinking a lot about gray goo and nanobots that kinda worried me because of the stories and science fiction. The class showed that there was more to nanotech than just dangers," "Now I won't believe all of the hype I read because I have an understanding of the background of nanotechnology," and "Before taking this course I had fallen for the overly ambitious vision of self-replicating robots transforming the world. Now I have a more pragmatic sense of the potential of nanotechnology." The discussion of these prevalent misconceptions is fascinating and will be explored in a subsequent publication. Moreover, the students expressed greater confidence in their ability to consider technology with respect to societal issues and in the judgment of various claims of nanotechnology to market consumer products *(25).*

Conclusion

This course was well-received and some good word-of-mouth advertising has resulted in continued student interest in the course. The half-semester format did not hinder the coverage of the topics listed in Table 1, however a full-semester will relax the course pacing.[2] A full-semester version of this course will allow for the addition of more sophisticated laboratory exercises, more molecular-modeling assignments, student-project presentations *(26),* a field trip to a modern research facility, and the introduction of scanning probe *(27)* and electron microscopy *(28)* experiences for the students. Invitations will be extended to incorporate the complementary contributions of faculty from a variety of departments and disciplines in an attempt to provide a more representative assortment of views concerning nanotechnology. The author has since developed and taught a modified version of this course as a full-semester first-year seminar and plans to offer a full-semester version of the original course. While nanotechnology has served as a promising example, the liberal arts approach described here is easily adaptable to other engaging interdisciplinary topics such as forensic chemistry, environmental chemistry, and materials chemistry, among others.

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[W]Supplemental Material

A student nanotechnology questionnaire, complete course reading list, course syllabus, BAT (Be Able To) learning objective lists, example of reading quizzes, example problem sets, and example in-class and take-home exam portions are available in this issue of *JCE online*.

Notes

1. Wabash College is a private, independent, four-year liberal arts college for men, granting the Bachelor of Arts degree. Wabash's 860 students come from 34 states and several foreign countries. Over the past 10 years, we have graduated an average of 12 chemistry majors per year. The College was founded in 1832 and is located in Crawfordsville, Indiana, a community of 14,000 located 45 miles northwest of Indianapolis, IN and 150 miles southeast of Chicago, IL.

2. While the majority of courses at Wabash College are full-semester courses, half-semester courses give Wabash faculty the ability to evaluate new course concepts and provide its students with the opportunity to fulfill distribution requirements by exploring a greater variety of topics outside of their major area of study.

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