P4. Engaging Liberal Arts Students Beyond Introductory Chemistry: A New Course in Nanotechnology

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ABSTRACT

The study and manipulation of matter on the nanometer scale is known as nanoscience or nanotechnology, an exploding field still in its infancy. Much of the driving force for building tiny devices and features on the nanoscale is their importance for existing and emerging technologies such as microelectronics, electromechanical systems, sensors, molecular computing, and a myriad of other applications. In response, we have designed a new course open to undergraduate students that have completed at least one semester of introductory chemistry, which focuses on the basic science behind the science fiction and the "hype." Nanoscience provides an excellent way of learning to look at the amazing opportunities that arise when various fields of science intermingle. We utilize this as an opportunity for applying the fundamentals we teach in our subdisciplinary courses to applications and problems with a broader scope. The course revisits the origins of the field and spotlights current advances. Utilization of a central text is supplemented by the use of the primary chemical literature as well as selected works of science fiction. Furthermore, students consider the social, political, economical, environmental, and ethical ramifications of a potential "nanotech revolution." In addition to lecture and discussion, students participate in laboratory exercises and a major writing assignment. This paper expands upon our recently published work (*J. Chem. Educ.* **2007,** *84*, 259.) highlighted in the Sept. 17th issue of *Chemical & Engineering News*.

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1. Nanoscience Education

As an integral part of the liberal arts, the sciences have much to offer our students. As liberally educated citizens, they must be given the opportunity to appreciate the nature and culture of scientific inquiry. In addition, chemistry provides a wealth of fascinating content that informs students about the composition of the physical universe, its origins, and our current understanding of the principles by which it operates. However, many students are intimidated or even fearful of science. A growing number complain about being “forced” to take lab sciences and sacrifice their summers taking some of these courses off-campus. In response, we have developed a new course that focuses on a popular interdisciplinary theme in an attempt to enhance student engagement.

Nanoscience and technology is quickly gaining the attention of the general public through media outlets and recent works of fiction [1]. Since the mid-late 1980s, nanoscience has transcended the confines of research laboratories to inspire popular works of science fiction. The study and manipulation of matter on the nanometer scale is known as nanoscience or nanotechnology, an exploding field still in its infancy [2,3]. While these terms are typically used interchangeably, nanoscience refers to the investigation of fundamental physical and chemical phenomenon at the nanometer size regime, whereas nanotechnology implies the application of these principles in the development of nano/microscopic devices and manufacturing processes. Unique, unpredictable, and highly intriguing physical, chemical, optical, and electrical phenomena can result from the confinement of matter to nanoscopic dimensions. The nanoscale size regime is measured in terms of nanometers, or billionths of a meter (Figure 1). Researchers generally agree that in order to classify a structure or device as “nano” it must exhibit dimensions measuring between one and one hundred nanometers [1]. Much of the motivation for building infinitesimal devices and exploring materials properties on the nanoscale derives from their importance for existing and emerging technologies. These include nanoelectronics, sensors, molecular computing, and medical diagnostics, among others [2,3]. Scientists, engineers, politicians, authors, filmmakers, and the general public are only beginning to consider the implications of the potential impact this new technology may have on modern society [1]. As educated citizens and voters, our students must do the same [4,5].

In response to the rapidly increasing significance of this interdisciplinary research field, a course was developed [4,5] to serve Wabash College [6] undergraduate students, regardless of major. The sole prerequisite required that students complete one semester of introductory chemistry prior to enrollment in CHE171, Chemical Nanotechnology. This course utilizes a liberal arts approach to focus on the fundamental science behind the major research initiatives of the field, science fiction, and the media hype. The overtly interdisciplinary nature of nanoscience and technology provides an exceptional opportunity to highlight the amazing opportunities that arise when various subdisciplines of science interact. Students are introduced to the origins of the field and challenged to consider the political, economical, environmental, and ethical concerns relating to nanotechnology and its potential impact on modern society. Lectures are coupled with guided discussions on prevalent course readings and students participate in a significant number of writing assignments, molecular modeling simulations using standard software packages, and a select number of guided laboratory exercises. A central text is supplemented by examples taken from the primary chemical literature as well as selected works of science fiction, film, and computer software.

2. Course Objectives

While the research accomplishments and impact of the field is acknowledged, this course emphasizes the interdisciplinary nature of nanoscience and technology through a liberal arts perspective. Although dedicated nanotechnology degree programs have recently been initiated at various institutions, the sustenance of such interdisciplinary efforts relies upon the contributions and collaborations of talented individuals across many disciplines. Interdisciplinary efforts cannot truly realize their full potential without contributions from collaborators drawing from sound expertise in a discipline. This course provides an opportunity to appreciate the remarkable accomplishments that arise when various fields of science and engineering converge. Nanoscience provides a wealth of prime examples for applying and reinforcing the fundamentals students learn in subdisciplinary courses to applications and problems with a broader scope. Likewise, the evolution and growing acceptance of this interdisciplinary field within the larger scientific community illustrates the human endeavor that is science and the collaboration of individuals from diverse backgrounds toward a common goal. Students often fall victim to the “tunnel vision” that results from a rigorous, specialized curriculum and may fail to appreciate the coursework of their major in context [7]. Furthermore, gaining an appreciation of other viewpoints may prepare students in becoming innovative chemists, biologists, physicists, and mathematicians by serving to provide them insights in attacking more traditional problems in the field through novel new approaches.

Although one of the prime motivations behind the development of this course involves reinforcing the fundamental science curriculum, the liberal arts approach demands that the interaction of science in the context of larger societal issues is emphasized. Current undergraduates incorporate digital technology into their daily lives more than any previous generation. Now, more than ever, the feverish pace at 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 opportunists that might unethically exploit the popularity of the subject for financial gain. As students participate in the political and economical decisions that will profoundly impact the future, it is imperative that they consider evolving science and technology through critical ethical and moral lenses. A serious commitment was made to identify and combat the variety of misconceptions surrounding the subject and to guide our students, as educated citizens, toward the consideration of the social, political, economical, environmental, and ethical issues related to nanoscience and technology. Utilizing this strategy, nanotechnology allows for a true liberal arts approach to an exciting and engaging interdisciplinary area of science and engineering.

3. Classroom Resources

In order to effectively engage undergraduate students, a genuine attempt was made to incorporate a diverse selection of classroom resources associated with nanoscience and nanotechnology. While a variety of books continue to illuminate the subject, most are either technical reference works aimed at graduate students and researchers in the field or focus solely on painting horrific or utopian visions of a future nano-revolution. In order to best serve the undergraduate audience, the adoption of a central text that bridged the intellectual gap between these categories was crucial to the success of this course. For this reason, *Nanotechnology: Basic Science and Emerging Technologies* was ultimately chosen [8]. The text successfully introduces the field, reviews the prerequisite introductory chemistry concepts, spotlights various research areas, and finally considers some of the social implications of nanotechnology. The text frequently does a sufficient job of breaking down the numerous acronyms and idiosyncratic vocabulary that permeates the field. Nanoscience concepts are often related to more fundamental concepts that undergraduates encounter in their introductory science courses. Molecular self-assembly, for example, is rationalized in terms of intermolecular forces and basic thermodynamic arguments familiar to the general chemistry student. The connection between nanoscience research and fundamental science was emphasized as a consistent theme of the course, which sought to engage student interest as well as demonstrate the creative ways their knowledge may be applied to problems with a larger scope.

In addition to the central text, a range of complementary sources were introduced as the course progressed. Reading assignments from *Scientific American* provided introductions and reviews of major nanotechnology research initiatives [9]. Students were then introduced to the primary literature through a variety of carefully selected articles from the American Chemical Society journal, *Nano Letters*. Articles were selected to provide examples of recent findings from many of the leading research groups in the field. A special effort was also made to select papers that were well-organized, demonstrated a clear use of the scientific method, and utilized writing styles and vocabulary that proved accessible to the students. These primary literature articles were distributed with a list of questions that prompted students to pay attention to the overall structure of a primary source as well as the particulars of the research methods and findings. In some instances, only the bibliographic information was supplied and students were given the opportunity to interact with library staff and searchable databases to obtain the assigned article. After each student was given time to read the article and complete the associated questions individually, the class engaged in a guided discussion that explored the article and its connections to previous course topics.

In order to provide a supplement to the significant science and research focus, the influential Drexler text, *Engines of Creation*, was assigned and discussed for its role in the popularization of the subject [10]. The text provided a convenient resource for transitioning classroom discussion from fundamental science to the potential impact of nanotechnology on society, ethical concerns, and the possible environmental consequences of modern research in nanoscience. Similarly, Michael Crichton's *Prey* [11] and other works of science fiction, such as John Robert Marlow's *Nano* [12], helped highlight many of these social issues and popular perceptions of nanotechnology. Three nanotechnology science fiction anthologies, *Nanodreams* [13], *The Nanotech Chronicles* [14], and *Nanotech* [15], served as a resource from which a diverse collection of fiction was obtained for classroom use. For example, Greg Bear's *Blood Music* [13,16], one of the first science fiction short stories to specifically relate to nanotechnology, and Kevin Anderson's *Dogged Persistence* [13] were utilized in motivating classroom discussions.

Video clips from several popular science fiction movies and television series were also utilized in the classroom to stimulate discussion relating to popular fears and misconceptions surrounding nanotechnology [17]. *The New Breed*, an episode of *The Outer Limits* television series [18], loosely based on Greg Bear's *Blood Music,* [13,16] portrays many of the popular fears and misconceptions of nanotechnology. Clips from *Virtuosity* [19], *Minority Report* [20], *I Robot* [21], *Path of Destruction* [22], *Teenage Mutant Ninja Turtles* [23], *Jimmy Neutron* [24], and a variety of *Star Trek* sources [25] were also used to drive classroom discussion. The number of references to nanoscience in the popular fiction is rapidly increasing [1] thereby exposing the general public, both young and old, to Hollywood's interpretations of nanoscience and technology. These examples were instrumental in demonstrating the origins and reinforcement of many prevalent misconceptions regarding the subject.

In addition, many computer software and internet resources were employed to engage the students. Molecular modeling using the PC Spartan Pro software suite [25] is integrated into every level of the Wabash College chemistry curriculum [26,27]. Capitalizing on the students' basic familiarity with the software, they were challenged to model and perform simple calculations for structures such as fullerenes and quantum dot structures. The Blackboard [29-31] course management software proved to be an invaluable tool in serving as the central nexus for course information, announcements, and 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) website [2]. Moreover, the Blackboard software allowed students to participate in online discussions, view their grades, obtain duplicate copies of lecture handouts, supplemental readings, problem sets, or laboratory handouts, and quickly communicate with the instructor or fellow students via e-mail. Finally, the classic PC real-time strategy game, *Total Annihilation*, allowed students to explore prevalent misconceptions of nanofabrication and disassembly in an interactive, yet entertaining environment [32,33].

4. Structure and Content

As a deliberate departure from traditional senior-level, special topics courses, any student having completed one semester of introductory chemistry was invited to enroll in CHE 171, Chemical Nanotechnology, offered for the first time in the spring of 2004. In keeping with the objectives of the course, students from various majors and classes were encouraged to participate. Enrollment consisted of four freshmen, four juniors, and two seniors of various majors, ranging from biology to religion [4,5]. The varied backgrounds, interests, and viewpoints of the students helped to reinforce the multifaceted survey of the subject. Course meetings were held twice a week and typically consisted of ~40 min of lecture and ~35 min of guided discussion focusing on an assigned reading or questions stemming from lecture topics. Material was selectively partitioned and presented as a series of four course units commensurate with the objectives of the course (Table 1).

4a Unit I: Nanoscience and Nanotechnology

During the first course meeting, students completed a "nano" survey (Figure 2) to gauge their initial perceptions and interests in nanoscience and technology. Next, course policies were discussed and the class viewed *The New Breed*, an episode of *The Outer Limits* television series [18]. The storyline of the program attempts to dramatically spotlight many of the popular fears and misconceptions of nanotechnology. The episode inspired a lighthearted, yet focused class discussion regarding the students' preconceived notions of the subject. Interest in this initial discussion was so great that students revived it after class utilizing the Blackboard course website online discussion option.

This discussion, along with the class survey, served to illuminate many of the common misconceptions of nanotechnology shared by the students. A majority of the students noted that "tiny robots" or "machines that you can't see" are the first images that come to mind when nanotechnology is mentioned. Prior to enrolling in the course, students encountered nanotechnology for the first time in motion pictures, cartoons, or cable television programs. With the exception of a few documentaries or news programs, the preponderance of exposure to the subject originated from science fiction programs with storylines that utilized nanotechnology as an antagonistic plot device. While this predominately negative view of nanoscience dominates the popular fiction, very few students voiced that the field would ultimately yield dire consequences for modern society. Concerns over military applications and environmental contamination were expressed, yet students were exceedingly optimistic in their perceptions of the field. In particular, the large majority of students listed significant advances in medicine as the ultimate promise of nanoscience and technology.

While there was considerable variation in their responses, students generally predicted that nanotechnology development is still anywhere between ten to fifteen years away from yielding products that will have a significant impact on their daily lives. However, certain products were mentioned, such as the cell phones, digital music players, sporting equipment, that students believed may already use nanotechnology in their production. The students perceived that the large bulk of funding for nanoscience research originates from government programs, as well as corporate product development, to a lesser extent. Subsequently, it was noted that students assumed this research is currently taking place at a feverish pace in a variety of institutions, ranging from public universities and corporate labs to "top secret military research facilities" and "think tanks." It was also very interesting to discover that the students ranked engineers, above biologists, chemists, physicists, and mathematicians, in their contributions to the development and understanding of nanoscience and technology. While these initial survey and discussion results yielded intriguing anecdotal data, no formal attempts were made to quantify student attitudes and perceptions of nanoscience and technology.

In addition to the class discussion, a brief historical timeline of nanotechnology was presented. By revisiting the origins of the field, students were shown that nanoscience has garnered the attention of researchers across the globe for some time under the classifications of condensed matter physics, surface science, and materials engineering, among others. Richard Feynman's seminal lectures [34] were briefly explored and served to reinforce the fact that the enthusiasm for exploring the nanoscale is nothing new.

4b. Unit II: Viewing the Nanoworld

Research in nanoscience, as reported in the primary literature, is generally displayed with heavy emphasis on electron and/or scanning probe microscopy [3]. Such visual data engage students on an analytical, as well as an aesthetic level. In relating the historical timeline of nanotechnology, presented in the previous unit, a conscious effort was made to spotlight the development of the electron microscope and scanning probe microscope. The second course meeting explored the instrumentation central to the characterization and manipulation of nanoscale materials. The fundamental limitations of traditional light microscopy were explained and naturally transitioned into a discussion of the general principles behind modern electron microscopy. Scanning probe microscopy was also 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 valuable morphological and topological data obtained from the respective techniques that have paved the way for modern nanoscience research. The importance of these characterization tools was further demonstrated by the presentation of prominent examples of micrographs taken from the primary literature. Students were challenged to critique both the advantages, as well as the limitations, of microscopy data. Using various imaging software tools, students discussed some of the inherent ethical concerns that arise when dealing with the manipulation and presentation of digital image data.

4c. Unit III: The Science Behind the Hype

The principal module of the course, consisting of six class meetings illuminated the fundamental science behind many of the key concepts and focus areas of nanotechnology. An introduction to the National Nanotechnology Initiative (NNI) highlighted the major interdisciplinary research initiatives in the field [2]. Classroom discussions focusing on 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. In-class and take-home problem sets challenged students to apply their previous science coursework to nanotechnology applications. For example, a problem might ask students to read a passage concerning self-assembled quantum dot formation and justify the spontaneous nature of the process in terms of enthalpic and/or entropic arguments.

Next, the fundamental science driving established and evolving nanofabrication methods was explored. Examples from biology, such as DNA and lipid bilayers, were utilized to explain and emphasize the importance of intermolecular forces and basic thermodynamics in molecular self-assembly processes [8]. The fundamental distinction between top-down and bottom-up fabrication strategies was discussed in detail, along with the inherent advantages and disadvantages of each. 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, spotlighting the fundamental science behind the nanotechnology. The unit concluded with a transition to focus on the potential applications of these materials and techniques in nanomedicine and future generations of micro/nanoelectronics and micro/nanoelectromechanical systems (M/NEMS). Homework assignments prompted students to explore internet resources to identify the various research groups at the forefront of nanoscience and technology research. The recent Smalley/Drexler debate highlighted the fact that the field is rapidly evolving and that viewpoints, even among proponents of the field, are quite diverse [35]. Finally, in an effort to provide a direct link to the realization of nanotechnology applications, an alumnus working toward the commercialization of recent research provided an insightful guest lecture for the students [36,37].

4d. Unit IV: Nanodreams and Nightmares

These course meetings, toward the end of the course, shifted student focus toward the consideration of the political, economical, environmental, and ethical issues related to a technology with such potential social impact. The potential benefits derived from future developments in nanotechnology were gleaned from a variety of fiction and nonfiction sources. Lecture supported classroom discussions 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 [2].

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-based products, and the infamous “gray goo” [10] 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 [11-25]. However, in order 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 [38-40]. Finally, in the concluding course meeting, students were encouraged to reflect on 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.

4e. Other Considerations

In addition to lecture and discussion, daily reading quizzes were conducted during the first ten minutes of random class meetings. These brief exercises were critical in identifying student misconceptions and were aimed at helping students in identifying the main concepts portrayed in the assigned readings. It afforded the instructor a tight feedback loop in planning class discussions and evaluation items. BAT (Be Able To) learning objective lists accompanied most reading assignments (Table 2). Four homework problem sets were distributed over the duration of the course, 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. These exercises also revisited topics of confusion, as identified by class discussions or reading quizzes.

Critical reading skills with respect to primary literature sources are essential in the pursuit of any area of study [41,42]. The importance of such skills was reflected in the exam structure for the course. Each of the two course exams consisted of two, separate sections. 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 classroom test taking by allowing them more time to carefully read and analyze the article of interest. The take home portion also emphasized science in consumer products, where students were challenged to critique suspect advertisements with exaggerated claims of nanotechnology.

Although the course did not have a dedicated, weekly laboratory session, two in-class laboratory periods were included as a complement to lectures and readings. Each laboratory activity was completed in place of a regular class meeting, so that scheduling external course meeting times was unnecessary. Students participated in two brief laboratory exercises: the preparation of citrate stabilized gold nanoparticles and preparation of an aqueous ferrofluid [43,44]. These were selected from a variety of high quality nanotechnology laboratory exercises suitable for undergraduates, produced by the Materials Research Science and Engineering Center (MRSEC) at the University of Wisconsin-Madison. A formal laboratory report was required for each exercise. In order 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 website 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 [45], a final paper assignment was assigned in place of a final exam. Students were given the choice of preparing an original 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 students 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. Paper 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 (10%), seven reading quizzes (10%), two laboratory reports (10%), and the final paper (20%).

5. Informal Student Feedback

Course evaluations and anecdotal evidence 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 in order 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 freshmen 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 seniors 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/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.

The students expressed that the course had drastically altered their initial 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 [46].

6. Conclusions and Future Directions

In conclusion, this course was well-received and 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 a bit. 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. A full-semester version of this course will allow for the addition of more sophisticated laboratory exercises, more molecular modeling assignments, student project presentations [47], a field trip to a modern research facility, and the introduction of scanning probe [48-51] and electron microscopy [52] 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 freshman 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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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 & Course Information
2	L: Nanostructures by Inference: Tools of the Trade D: Drexler and Feynman	Stix Article [9] Drexler, Chap. 1−3 Wilson, Sect. 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 [13] Wilson, Sect. 2.11, 6.3, 2.12
4	L: Molecular Self-Assembly II: Nature Shows the Way D: Nanofabrication	Whitesides/Love Article [9] Drexler, Chap. 4−5 Wilson, Sect. 6.1−6.8
5	L: Molecular Machines: Synthetic Mimics D: Michael Crichton’s *Prey*, Intro−139	Crichton, pp. 1−139 Astumian Article [9] Wilson, Sect. 5.1−5.15
6	L: Nanoparticle Materials: Colloids Reborn D: Smalley / Drexler Debate	Drexler, Chap. 6,10 Wilson, Sect. 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 & Lieber Articles [9] Wilson, Sect. 8.1−8.10
10	L: Group IV (C,Si,Ge): Buckyballs, Nanotubes, and Nanowires D: Nanomedicine	Alivisatos Article [9] Drexler, Chap. 7−9 Wilson, Sect. 4.1−4.9
11	L: Future Directions and Hopes (NanoDreams) D: Michael Crichton’s *Prey*, 139−335	Crichton, pp. 139−335 Wilson, Sect. 9.1−9.11
	L: Nanotechnology Dangers (NanoNightmares)	*Blood Music* [13,16] and *Dogged Persistence* [13]

12	D: Hopes and Consequences of Nanotech	Drexler Chap. 11-12 Wilson, Sect. 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*, 335−502	Crichton, pp. 335−502 Drexler, Chap. 13−15

Table 2. Chemical Nanotechnolgy BATs (Be Able To's) for Exam 1

1/27/04 − Lecture and Lecture Handout, *Self-Assembly: Order from Chaos*
1) Compose a working definition of molecular self-assembly with respect to nanofabrication. 2) Explain the concept of spontaneity as it relates to self-assembly and free energy. 3) Describe the intermolecular forces involved in driving self-assembly. Make sure you can identify the type of intermolecular forces involved in a given example. 4) Give one or two examples of self-assembly in biology and artificial structures.
1/27/04 − Pre-NNI, Andrews Handout, *Nanotech and Nanominds*
1) Give a general description of Andrews' experience with the early stages of nanotechnology thinking in Washington. 2) Describe his attitude toward the early reception Drexler received in Washington.
1/27/04 − NNI Handout, *Small Wonders, Endless Frontiers*
1) Give a brief description of the National Nanotechnology Initiative (NNI). 2) Describe the trend in funding support for research in nanotechnology. 3) Give a one-two line history of the NNI. Name the administration that passed it and the year it was passed. 4) Note some of the societal implications of the NNI. 5) Describe one of the important areas for investment and explain why you think it warrants funding.
1/27/04 − Wilson, Sections 2.11, 6.3, & 2.12
1) Compose a working definition of molecular self-assembly with respect to nanofabrication. 2) Explain what a SAM is and why they form. Name some common surfaces and molecule types used in SAMs. 3) Describe Dip-pen nanolithography and how it may be used for nanofabrication.

Figure 1: Putting the nanoscale into perspective

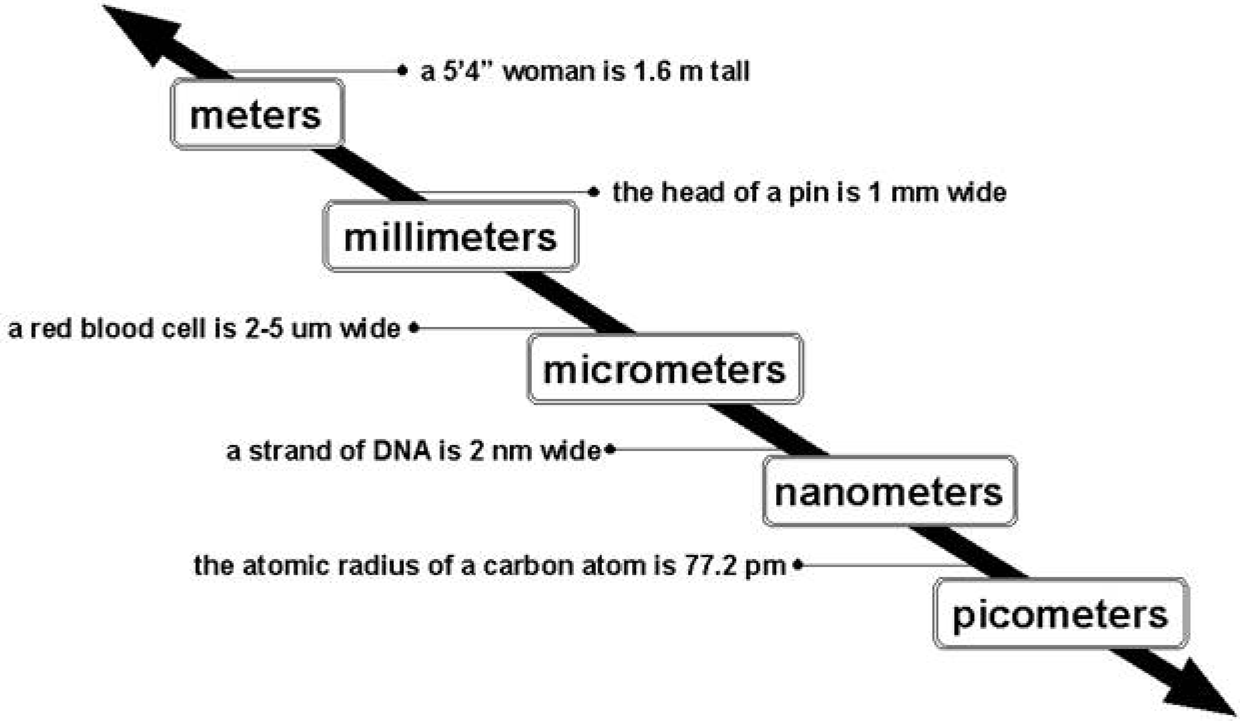

Figure 2: The nanoscience and nanotechnology survey taken by the students

"Nano" Survey

Please take a couple of minutes to complete the following survey. Please answer the following questions thoughtfully and very honestly. There is no need to place your name on this form.

1. When nanotechnology is mentioned, what is the first thing/image that pops into your head?

2. Using your own words, define ***nanotechnology***.

3. Had you heard about nanotechnology prior to signing up for this course? If so, describe the first time you heard about nanotechnology below.

4. Please list any books, movies, video games, or television that you remember referring to nanotechnology (even if only briefly).

5. Please describe **THREE** fears you have about nanotechnology and the future.

6. Please describe **THREE** hopes you have about nanotechnology and the future.

7. Do you believe that nanotechnology will eventually lead to more benefits or more perils for society? Briefly explain.

8. How many years do you believe it will take in order for nanotechnology to make a significant impact on your life? Briefly explain.

9. Can you think of any commercial products that are currently available which incorporate nanotechnology? Please list any that you can think of.

10. In your opinion, why are so many scientists and engineers so motivated to study nanotechnology?

11. In the boxes below, rank the following groups in order of ***increasing*** contributions to the development of nanotechnology. Explain your rankings below.

Biologists Chemists Engineers Mathematicians Physicists

12. Research into nanotechnology costs a great deal of money; where do you believe the majority of the funding comes from?

13. Where do you believe most of the research in nanotechnology is being conducted?

14. What is a ***nanometer***?

15. If you could send a single question to an expert in nanotechnology, what would it be?

16. Personally, why are **YOU** interested in nanotechnology?

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