TOWARDS A SUSTAINABLE APPROACH TO NANOTECHNOLOGY

by Integrating Life Cycle Assessment into the Undergraduate Engineering Curriculum

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Nanotechnology is poised to become a critical driver of economic growth and development for the early 21st century. It emerges from the physical, chemical, biological, and engineering sciences, where novel techniques are being developed to probe and manipulate single atoms and molecules. At a worldwide scale, most scientists and engineers are now confident that nanoscience and nanotechnology will revolutionize medical, industrial, agricultural, and environmental research.

Because of the expected impact of nanotechnology, aspects of the field are being actively incorporated into undergraduate curricula at various colleges and universities. Strategies employed in the integration of nanotechnology range from incorporation of modules on nanotechnology into existing courses[1,2] and development of new courses[3,4] to establishment of nanotechnology concentration areas within traditional engineering programs[5] and even creation of nanotechnology departments offering degrees in nano-engineering.[6,7]

Most individual courses on nanotechnology focus on manufacturing and application aspects of nanotechnology, while its environmental impacts are either discussed very briefly or not at all. It is increasingly recognized, however, that the development of nanotechnology should be accompanied by parallel efforts to investigate its potential health and environmental effects.[8] Although research on the health and environmental impacts of engineered nanomaterials (ENMs) is still in its infancy, it is fast growing[9-20] and it is imperative that engineering students are exposed to its most current findings.

Impacts of nanotechnology on the environment and health are discussed in comprehensive nanotechnology programs, such as the Nanotechnology Processes track offered by the Chemical Engineering Department at the Oregon State University[5] and the NanoEngineering B.S. program offered by the Department of Nanotechnology at UC San Diego.[6] Participation in these programs requires a long-term commitment from the students and it would be desirable to offer

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a single course or a short course sequence that would expose interested students to manufacturing and application of ENMs, as well as their environmental impact.

To meet this objective, we developed a sequence of two courses that introduce engineering students to different life-cycle stages of ENMs. The courses were offered in the Fall 2008 and Spring 2009 semesters and provided students with a solid foundation of nanoscale science and technology as well as the anticipated environmental challenges associated with their development. The ultimate goal of these courses, however, is to prepare the undergraduate engineer to not only recognize the need but also to be able to design nanomaterials into commercial products with the environment and public health in mind.

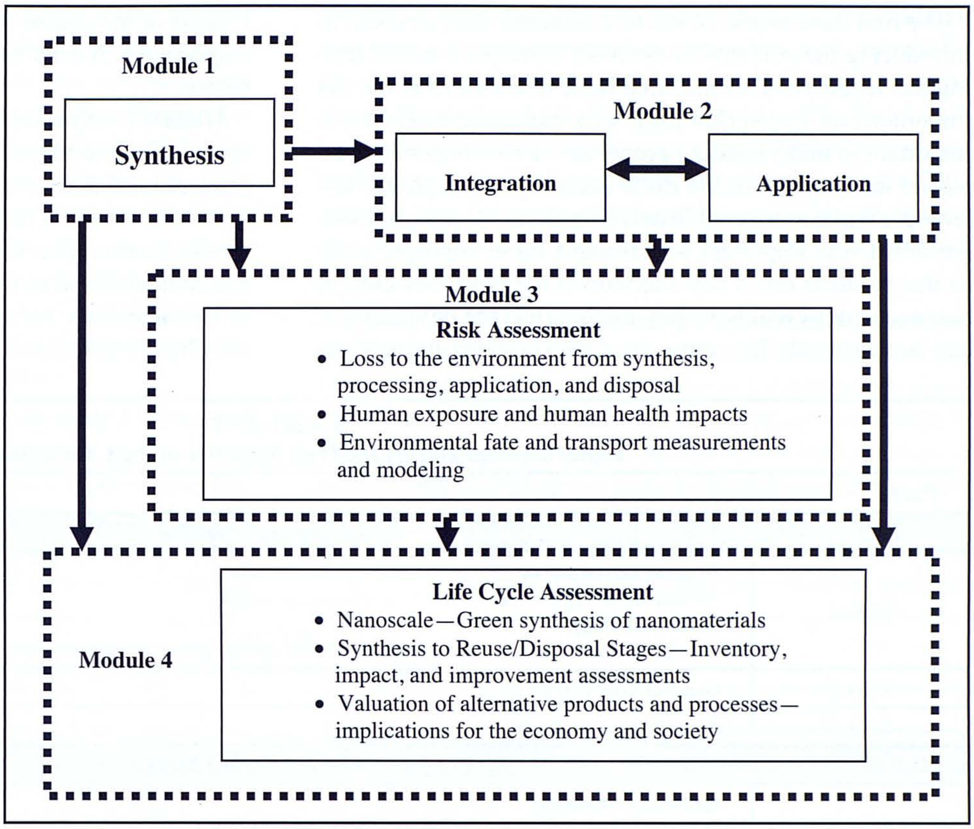


Figure 1. *Conceptual model for the development of learning materials. Module 1 focused on the synthesis of ENMs; Module 2 emphasized the integration and application of ENMs; Module 3 dealt with the environmental and health risks (i.e., exposure, toxicity, fate, and transport); and Module 4 defined the life cycle assessment (LCA) framework for the developed courses.*

In these courses, the environmental aspects of nanotechnology are introduced using the life-cycle assessment (LCA) framework. LCA is a systematic method of assessing the environmental and health impacts of product systems and services, accounting for the emissions and resource uses during the extraction and processing of raw materials and the design, production, distribution, use, reuse, recycle, and disposal of a product or function.[21-24] The LCA approach includes the following steps:

- *Scoping and goal definition (establishing the boundaries and objectives of the model),*
- *Inventory analysis (acquiring necessary inputs and outputs),*
- *Impact assessment (computation of the environmental and health effects),*
- *Improvement analysis (determination of the sensitivity of the variables in the model on the impacts and assessment of model robustness), and*
- *Valuation and decision-making (interpreting the results transparently).*

The U.S. EPA recently expressed the need for LCA in the design stage of nanomaterials[25] and many corporations and non-government organizations are following suit.[26] Introducing a life-cycle view of ENMs into the undergraduate curriculum allows students to become exposed to an environmentally conscious design, environmental literacy, and the beyond-the-plant aspects of this new technology just before they enter the job market or graduate school. Although LCA was incorporated into some chemical engineering courses, such as the Heat Transfer course,[27,28] to the best of our knowledge, the LCA framework has not been applied to any courses on nanotechnology.

COURSE DESCRIPTION

Figure 1 shows the organization of the course sequence. The sequence is focused on four conceptual modules: (1) Synthesis of nanomaterials; (2) Integration of nanomaterials and their applications; (3) Risk assessment; and (4) Life cycle assessment. The first semester (Part I) primarily covered the concepts in module 1 and the integration aspects of module 2. The goal of the first semester was to provide students with the scientific foundation of nanomaterial properties and the forces that act on nanoparticles. The second semester consisted of the remaining modules, which emphasized environmental and health implications of nanotechnology, as well as an understanding of LCA approaches and sustainable development of this emerging technology. More importantly, the LCA component pulled together the different course components by modeling the impacts from the entire life cycle.

The first three weeks of the first semester were devoted to introducing the students to the basic concepts covered during the sequence. This included basic discussions about the importance of nanotechnology, why molecular modeling is important to understanding properties of nanomaterials, and a brief introduction to life cycle analysis. Although this latter topic was not covered in detail until the second semester, we felt it was important to introduce these concepts early so that students could pay attention to the processes used in nanotechnology and how they might affect the environment and human health. The remaining topics covered during Parts I and II of the course sequence are shown in Tables 1 and 2, respectively. A brief description of each module is provided below.

Module 1—Synthesis of Engineered Nanomaterials: This module first introduced students to the unique size-dependent properties of nanomaterials and their qualitative difference from bulk materials in the *Physiochemical & Modeling Background section*. The students were introduced to experimental and computational techniques for characterizing the properties of nanomaterials. An emphasis was placed on understanding the physics associated with the materials' properties. Once

TABLE 1
Topics Covered During the First Semester of the Course Sequence

Part I	
	Course Sequence Overview
Week 1	**General Introduction** • Nanotechnology within life cycle assessment principles **Nanotechnology** • Why nanotechnology • Length scales • Bottom-up/top-down • Characterization
Week 2	**General Concepts of LCA**
Week 3	**Toxicological methods**
	Physicochemical & Modeling Background
Week 4	**Molecular Modeling** • Equations of motion-continuum vs. molecular models • Potential functions • Types of intermolecular and interatomic interactions
Week 5	**Analysis of Simulations and Overcoming Timescale Limitations** • Probability distributions and correlation functions • Potential of mean force (PMF) • Methods for calculation of PMF
Week 6	**Interactions Between Particles in Solution** • Van der Waals and Electrostatic Interactions • DLVO Theory • Solvation and Steric Forces
Week 7	**Introduction to Quantum Mechanics** • Photoelectric effect • Wave-particle duality • Schrödinger equation • Particle in a well
Week 8	**Solid State Physics** • Confinement effects • Quantum wells, wires, and dots • Semiconductors • Band structure
Week 9	**Optical Properties** • Bandgap • Exciton • Emission spectra
	Synthesis of Nanoengineered Materials
Week 10	**Surfactant Self-assembly** • Thermodynamics • Packing considerations • Preparation of templates • Relevance to biomembranes
Week 11	**Nanoparticle Growth** • Desired traits • Thermo/kinetic approaches • Aerosol • Microemulsion • Templates • Sol-gel • Arrested growth
Week 12	**Nucleation and Growth** • Chemical potential • Phase diagrams • Supersaturation • Homogeneous nucleation • Heterogeneous nucleation • Nucleation of crystals • Nucleation rate • Ostwald Ripening
Week 13	**Nanowire Growth** • VLS • Templates • Heterostructures
Week 14	**Carbon Nanotubes** • Relationship between geometric structure and electronic properties of nanotubes • Growth methods • Functionalization
	Integrating Nanomaterials
Week 15	**Dispersion** • Stability **Separations** • Purification • Size fractionation • Separation of carbon nanotubes
Week 16	**Nanomaterial Properties and Toxicity Implications**

the students had an adequate understanding of the physiochemical properties, the *Synthesis of Nanomaterials* for use in engineered devices and applications was covered. This section built upon the fundamental knowledge covered in chemistry and physics courses as well as strengthening the students' knowledge of reaction kinetics, diffusion, and fluid and heat flow in their application to problems unique to the synthesis of nanomaterials. New concepts, such as crystallization, were also introduced. The students were introduced to a wide variety of nano-sized building blocks, including micelles and microemulsions, nanoparticles, and 1-D nanostructures, such as nanowires and carbon nanotubes.

Module 2—Integration and Application of Engineered Nanomaterials: This module focused on the manipulation and integration of ENMs into devices and applications. The first section, *Integrating Nanomaterials*, strengthened the student's knowledge on separations, diffusion, and self-assembly processes while introducing the new concepts of interfacial phenomena, dispersion, and colloids, which play an important role in the integration of nanomaterials into useful devices and applications. Students were later exposed to the nanotechnology potential in a wide variety of fields, including microelectronics, manufacturing, information technology, healthcare, biotechnology, energy, and materials science. This material was covered in the *Applications of Nanomaterials and Implications for Human Health and the Environment* section (see Table 2).

Module 3—Risk Assessment of Engineered Nanomaterials: Understanding the effects of exposure to nanomaterials and their environmental fate and transport is fundamental in determining the overall environmental impact of nanotechnology.[8] This is challenging, however, as the industrial landscape is growing and changing very rapidly. In addition, ENMs could enter the environment from different stages along their life cycle. The *Potential Fate & Transport of Nanomaterials* in the Environment section of Module 3 was focused on the potential

TABLE 2
Topics Covered During the Second Semester of the Course Sequence

Part II	
	Potential Fate & Transport of Nanomaterials in the Environment
Week 1	**Environmental Pollution and Concepts in Pollutant Behavior** • Introduction • Connectedness of the geospheres and fate of pollutants
Week 2	**Physicochemical Parameters** • Aqueous solubility and factors influencing solubility • Phase partitioning • Physical/chemical interactions
Week 3	**Nanoparticle Transport in Porous Media**
Weeks 4 & 5	**Properties of Materials and Environmental Fate** • Transport in aqueous and soil systems • Pollutant interactions with cell membranes • Predictive approaches/tools • Bioaccumulation, biotransformation, bioepuration • Food transfer and biomagnification
Week 6	**Framework for Environmental Toxicology and Toxicity of Nanomaterials** • Toxicity testing • Typical toxicity methods • Routes of exposure and mode of action
Weeks 7 & 8	**Possible Mechanisms of Nanoparticle Toxicity** • Toxicity of nanomaterial synthesis • Physicochemical characteristics of nanomaterial and potential toxicity • Predictive approaches/tools • Green nanomaterial manufacturing and toxicity elimination
	Applications of Nanomaterials and Implications for Human Health and the Environment
Week 9	**Nanocomposites** • Dispersion • Polymerization (carbon nanotubes) **Thermoelectrics** • Nanowire- and quantum-dot based nanomaterials **Solar Cells** • CdSe hybrid • Dye-sensitized solar cells (TiO_2, ZnO) **Medical Applications** • Gold nanoshells • Carbon nanotubes • Sensors **Green Design and Environmental Implications**
	Life Cycle Assessment (LCA): Overview and Methodology
Weeks 10 – 12	**Metrics of Sustainability** **Stages of LCA** • Inventory analysis • Impact analysis • Sensitivity analysis **Case Studies**
Weeks 13 & 14	**Modeling Approaches** • Manual Approaches • Software (Simapro, TRACI, GaBi, Athena, Umberto) • Limitations of Modeling
Weeks 15 & 16	**LCA Application to Nanotechnology** • Nanotechnology-related Case Studies • Closing the Loop • Defining "Sustainable Nanotechnology" • Nanomaterial design and modeling

impacts of ENMs on the environment, their environmental mobility, reactivity, bioavailability, and toxicity. Specifically, the available experimental models to characterize the toxic potentials of ultrafine particles and the fate of nanomaterials after their intentional and/or non-intentional introduction to soils and aquatic systems were discussed. This subsection emphasized both the dispersal and ability of nanomaterials to move from points of release to far away locations and to encounter living organisms. The physicochemical properties that make ENMs commercially attractive were also evaluated for their potential risks to environmental and human health. Finally, the students were introduced to the lack of adequate experimental data to understand the nano-toxicological effects and how molecular modeling can play an important role in advancing our knowledge of these effects.

Module 4—Life Cycle Assessment (LCA): This module taught students the fundamentals and methodology of LCA construction with a specific emphasis on the synthesis, processing, application, and disposal life-cycle stages of ENMs addressed in modules 1 – 3. The introductory material educated students in LCA development and reinforced the connection between the synthesis, processing, application, and disposal stages with potential environmental concerns. Students also learned how impacts are calculated using various methods, including the Environmental Risk Evaluation method presented by Allen and Shonnard,[29] the Argonne National Laboratory GREET model that deals with transportation impacts,[30] and other methods included in the modeling software discussed below. All steps of LCA recommended in the ISO 14040 guidelines[21] were thoroughly discussed with case studies of existing LCAs, along with development of an LCA framework to compare traditional processes with alternative green nanotechnologies reported in the recent literature (*e.g.*, see References 31 and 32). Students were then introduced to various LCA modeling software packages, including SimaPro (Pré Associates, The Netherlands) and TRACI (developed by the U.S. EPA and available as freeware from the agency's website, <www.epa.gov>). As a final section in this module, the implications of nanotechnology were discussed from a life cycle perspective. As data from many stages of the life cycle of nanomaterials were limited and not all impacts of these materials can be predicted, the students were challenged to construct wise approaches for handling these technologies throughout their life cycle and for developing wise policies and regulations.

COURSE IMPLEMENTATION

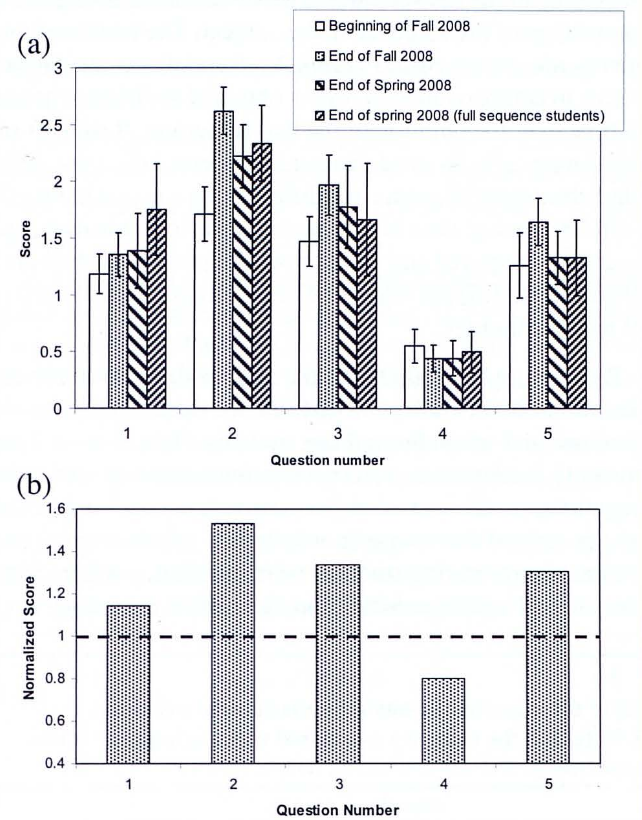
The course sequence was offered during the 2008–2009 academic year. Course materials were developed to target senior undergraduate students, because, at this stage in the curriculum, engineering students from all disciplines have been exposed to the necessary fundamental concepts in chemistry, physics, thermodynamics, heat transfer, transport phenomena, mechanics, numerical methods, and computer programming. Therefore, developed course modules were designed to build upon these concepts and expand students' mastery of these subjects into this emerging discipline. Although the developed courses were designed for undergraduate students, interested graduate students were also allowed to enroll. A textbook on basic nanotechnology principles[33] was required for Part I while research articles and case studies were used for Part II.

All four instructors attended the first two weeks of the semester to emphasize the course's framework and the connectedness of the different modules. After this general introduction section, each of the two developed courses was taught primarily by two instructors (*e.g.*, Ziegler and Kopelevich for Part I and Bonzongo and Lindner for Part II). The instructors attended lectures during both semesters, except when lecture times conflicted with other professional events. A student-centered teaching approach was used in both courses. This method varies from the traditional approach that relies on the belief that ideas can be successfully transferred by simply telling them to the students. The student-centered approach is based on the premise that students have better retention when they are actively engaged and the approach relies on self-managed teams that work collectively on Process-Oriented Guided-Inquiry Learning (POGIL) activities. The POGIL approach helps students develop teamwork, communication, and management skills while engaging in critical thinking and assessment as they sharpen their problem-solving skills. This focus on soft skills is particularly effective at educating students on the higher-order cognitive tasks of the Bloom taxonomy.[34]

The following POGIL activities were incorporated into the course sequence:

Computational Experiments to Explore Nanoscale Phenomena. These phenomena are not familiar to the students from everyday experience or from the core chemical and environmental engineering classes that traditionally focus on macroscopic phenomena. In order to provide students a hands-on experience with nanoscale systems, we introduced molecular dynamics simulations (MD) into Part I of the course sequence. MD simulations were performed using the Molecular Workbench software package.[35] This open-source package was specifically designed for educational purposes. It enables students to start performing MD simulations with minimum background. It employs a simplified molecular model that nevertheless retains relevant physics. This enables students to (i) perform simulations on their personal computers within a reasonable amount of time and (ii) explore effects of various molecular properties (such as charge, degree of hydrophobicity, etc.) without being overwhelmed with details of more accurate models. The students performed molecular dynamics simulations to investigate nanoparticle nucleation, interactions between colloidal nanoparticles, and self-assembly in solution.

Open-ended Design Problems. Several open-ended assign-



A1. What is special about the nanosize of particles?
A2. What types of forces dominate at nanoscale? List as many as you can.
A3. What new challenges arise in manufacturing of nanomaterials?
A4. What are the main differences between macro- and nano-scale transport processes?
A5. What are the benefits and limitations of modeling versus experimental approaches?

***Figure 2. (a.)** Average scores corresponding to each question over the two semesters. Answers to questions were lists of various nanomaterial properties. Therefore, the grading scale was 1 point for every correct item on the list. Here and in the following plots, "full sequence students" refers to the students who have taken both semesters of this class. **(b.)** Score of each question at the end of the fall semester normalized to the beginning of the sequence.*

ments asked students to design a novel device or an experiment. For example, in order to reinforce students' knowledge of interparticle interactions, the students were asked to investigate possible applications of nanorod electrodes as computer memory elements and nanorelays. In another assignment, the students were asked to design an experiment to investigate production of the reactive oxygen species (ROS) by fullerene nanoparticles and the ROS effects on living organisms.

Critical Literature Reviews and In-Class Discussions. In Part I of the course sequence, the students were asked to perform a critical review, write a report, and make a presentation on various methods of nanoparticle synthesis. The synthesis aspects discussed by the students included raw materials, physical conditions, quality of the final product, and potential health and environmental hazards. In Part II of the course sequence, the students prepared and delivered presentations based on peer-reviewed papers related to LCA of nanomaterials. Some of the papers assigned by the instructor did not address LCA directly and the students were asked to identify and comment on aspects of the paper relevant to LCA. We also organized an in-class discussion regarding viability of nanobots following the Smalley-Drexler debate.[36] The discussion was guided with specific questions that forced the students to argue about the scientific merits of the ideas.

ASSESSMENT METHODS

While no one single effective tool for assessing learning and/or evaluating innovations in higher education exists, a combination of several methods can be used to capture data from both cognitive and affective domains and provide unique information that bridges that of traditional assessment tools, such as exams, quizzes, and student evaluations. Many of these traditional assessment tools generally cover only a narrow range of course content and are not well suited for assessing higher-level understanding and skills. Ideally, an efficient assessment tool should provide[37]: (i) formative assessments of student understanding; (ii) reliable, quantifiable data about student understanding; and (iii) data useful to students' cognitive and meta-cognitive growth. In addition, faculty should be able to use such a tool to evaluate their effectiveness and the advantage of additions or changes to existing curricula or programs.

The following two approaches were used to assess the outcomes from the course sequence:

Evaluation via knowledge surveys: Knowledge surveys consisted of numerous items that covered the full breadth of course learning objectives and levels of understanding. Students completed the survey at the beginning of the first 2008 semester and at the end of each semester. Surveys at the beginning of a course provided information on students' background and preparation. During the course, surveys became learning guides for the instructors, helping them make necessary adjustments on both teaching style and exam format/content to improve student learning.

Student course evaluation: In general, the focus of this tool is on whether or not students are satisfied or dissatisfied with the entire course and/or individual modules. While this is useful information, this process can also be used to explore more complex and, perhaps more relevant issues, such as what students are learning, what aspects are more useful, what could be improved, etc.

ASSESSMENT RESULTS

Student enrollment: The two courses attracted a larger number of students than originally expected. We also admitted students who could not commit to the entire sequence of two courses due to graduation and other scheduling conflicts (see below). The latter had a negative impact on the number of students providing feedback on the course sequence as a whole. Further details on student enrollment are provided below.

PART I: Fall 2008 – A total of 19 students registered for the fall course of the sequence. Enrolled students included eight graduate and 11 undergraduate students. The graduate students attracted by this offering were those conducting research on different aspects of nanotechnology and all were environmental engineering majors. The undergraduate group included four students from environmental engineering and seven from chemical engineering. The first survey was administered at the beginning of the fall semester to probe the initial background knowledge of the students on the subject. The results of this survey are presented in Figures 2 – 5 and discussed further below in comparison with results obtained at different points in time over the duration of the two semesters. Results from this survey also showed that some students could not complete the course sequence for different reasons, including (i) Fall 2008 being their last semester prior to graduation, (ii) course not required and would not fit in pre-established plan of study, and (iii) not interested in the environmental aspects of nanotechnology.

PART II: Spring 2009 – At the start of the second semester, a total of 12 students registered for the course, with six graduate and six undergraduate students. Only nine of these students participated in surveys administered at either the beginning or the end of the semester, however. Unlike the first portion of the course in which only environmental and chemical engineering students were enrolled, students from electrical (1 undergraduate) and agriculture & biological (1

TABLE 3
Students were asked to assess their own ability to address each of these aspects in solving unstructured problems. Students' responses to these questions are summarized in Figure 5. Note that the category associated with each question was not given to the students.

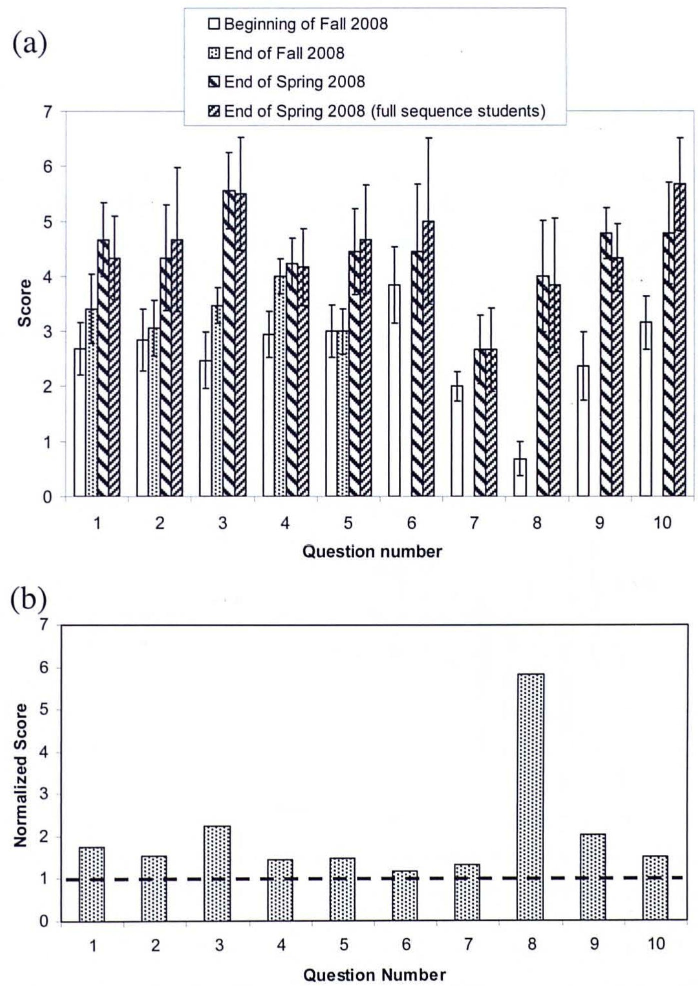
Question #	Categories	Questions
D1	Need recognition	State the needs of the problem in clear and explicit terms
D2		Recognize the needs to be addressed by the problem
D3	Problem definition	List the performance requirements that a solution must satisfy
D4		Establish criteria for evaluating the quality of a solution
D5	Planning	Develop a solution strategy given a model of the design process
D6		Divide a problem into manageable components or tasks
D7	Information gathering	Identify the knowledge and resources needed to develop a solution
D8		Ask probing questions to clarify facts, concepts, or relationships
D9	Idea generation	Describe procedures or techniques to search for and generate solutions
D10		Generate possible alternative solutions
D11	Modeling	Select a mathematical model that can be used to characterize a solution
D12	Evaluation	Identify the pros and cons of possible solutions
D13		Compare a set of solution alternatives using a specified set of criteria
D14	Feasibility analysis	Analyze the feasibility of a solution
D15	Selection	Select a solution that best satisfies the problem objectives
D16	Documentation	Document your solution process
D17	Communication	Understand the different roles and responsibilities of being an effective member in a team
D18		Resolve conflict and reach agreement in a group
D19		Identify the characteristics of effective communication
D20	Iteration	Recognize when changes to the original understanding of the problem may be necessary
D21		Suggest modifications or improvements to a final solution
D22		Develop strategies for monitoring and evaluating progress
D23	Implementation	Build a prototype or final solution

graduate) engineering departments registered for the course as well. Four out of nine students who participated in the surveys during the spring semester (Part II) did not take Part I of the course sequence.

Course objectives: Questions related to the general aspects of the course sequence and students' responses at various points during the sequence are shown in Figures 2 – 5 and Table 3.

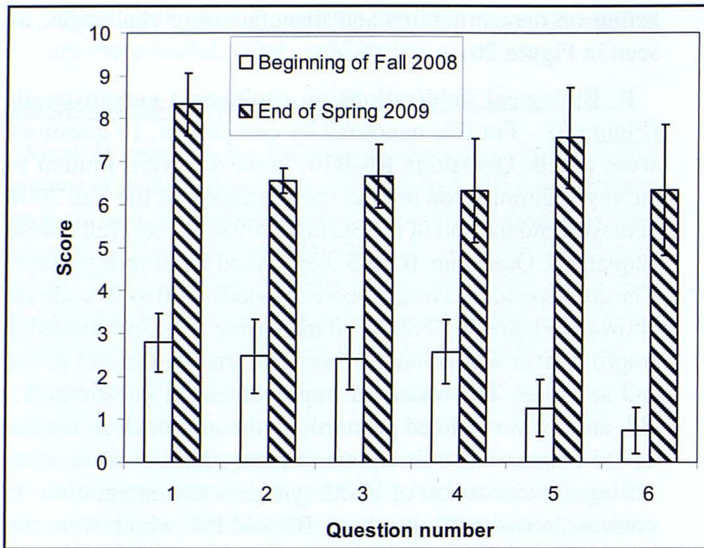
A. Properties of engineered nanomaterials and modeling of nanoscale processes (Figure 2, page 123) – These topics were covered in Part I of the course sequence. Therefore, the students who took only Part II had limited knowledge of these topics. Hence, we focus on comparison of the students' knowledge at the beginning and the end of the fall semester. With the exception of question A4 (differences between macro- and nano-scale transport processes), the results shown in Figure 2a indicate clear knowledge improvement by the end of the first semester. The most significant improvements were observed in the students' understanding of the forces acting on nanostructures and manufacturing challenges, as seen in Figure 2b.

B. Biological implications on engineered nanomaterials (Figure 3) – For this nanotoxicity component, 10 questions were asked. Questions B6-B10, however, were limited to surveys administered only at the beginning of the Fall 2008 semester and the end of the Spring 2009 semester (full course sequence). Questions B1-B5 were asked in all four surveys. The corresponding average scores graded on a 0 to 10 scale are shown in Figure 3a. Overall, an increasing trend in knowledge improvement was observed from the start to the end of the fall semester. The observed improvement in questions B1, B3, and B4 was related primarily to the introductory section of the course with subsequent reinforcement of these ideas during the discussion of ENM synthesis and integration. In contrast, answers to questions B2 and B5, which were not covered in the first course of the sequence, showed no knowledge improvement. When scores obtained at the end of spring semester are compared to scores recorded at the beginning of



B1. How would one combine chemical synthesis, modeling, & toxicology to produce green ENMs?
B2. Discuss very briefly the potential for the release of engineered nanomaterials to different environmental compartments as they are processed from cradle to grave.
B3. What properties of ENMs may affect their toxic effects? Name as many properties as you can.
B4. Based on the size and physicochemical properties of ENMs, could you list potential negative impacts of ENMs on the environment?
B5. Why do we need to assess the environmental and health impacts of ENMs separately from their bulk counterparts – In other words, why can't we simply use knowledge of toxicity of bulk materials to predict the toxicity of ENMs?
B6. What is environmental chemodynamics and how does it apply to ENMs?
B7. What types of transformations ENMs might undergo if released to the environment?
B8. Solvent partitioning has been used to predict the potential for bioaccumulation and toxicity of xenobiotics. What difficulties would you anticipate from the use of solvent/water distribution in assessing the potential for bioavailability and toxicity of ENMs?
B9. What key factors affect toxicity measurements? Name as many as you can.
B10. What could be the potential targets of ENMs in (i) animal, (ii) plant, and (iii) microbial cells? Explain.

***Figure 3.** (**a.**) Average scores for answers related to the toxicity aspects of engineered nanomaterials. The grading scale for these questions is 0 to 10. (**b.**) Score of each question at the end of the spring semester normalized to the beginning of the sequence.*



C1. Name the three stages of life cycle assessment (LCA) development.
C2. Select a specific nanomaterial and list the life cycle stages of this ENM.
C3. Identify, even in general terms, the relevant inputs and outputs of each life cycle stage.
C4. Identify the environmental impacts of interest and defend your selection.
C5. Identify the primary uncertainty of your LCA model for your selected nanomaterial.
C6. What would be the best software to use in performing the LCA of your ENM? Explain why.

Figure 4. *Average scores for answers on LCA questions. The grading scale for these questions is 0 to 10.*

fall semester, a significant knowledge improvement is observed as shown in Figure 3b.

C. Life-cycle assessment (Figure 4) – This section of the course sequence offered the opportunity for students to discuss the implications of nanotechnology from a life cycle perspective. Students considered the ethics of nanomaterials use, regulatory needs, international policies on nanomaterial use, and best practices for corporations in making decisions concerning nano-products, with the ultimate challenge of how to produce high-performance materials that pose no risk to the environment or public health. Only questions emphasizing knowledge of the basic steps of the LCA approach and tools used in LCA studies were asked in the survey administered at the beginning of the fall semester and at the end of the spring semester, however. These questions and the average scores corresponding to correct answers (graded on a 0 to 10 scale) are shown in Figure 4.

Unlike most physicochemical and biological concepts that are familiar to engineering students, LCA was a rather new topic to students enrolled in this sequence of courses. In fact, besides the few hours of LCA lectures as part of the general introduction during fall semester, most students enrolled in the course had no prior background in life cycle assessment. Therefore, they did not know how this discipline could be used to study the environmental implications of materials from cradle to grave. Accordingly, students' answers to the above questions were simply mere speculations and best guesses at the beginning of the fall semester. Answers to the same questions at the end of the course sequence (Spring 2009) show a significant knowledge im-

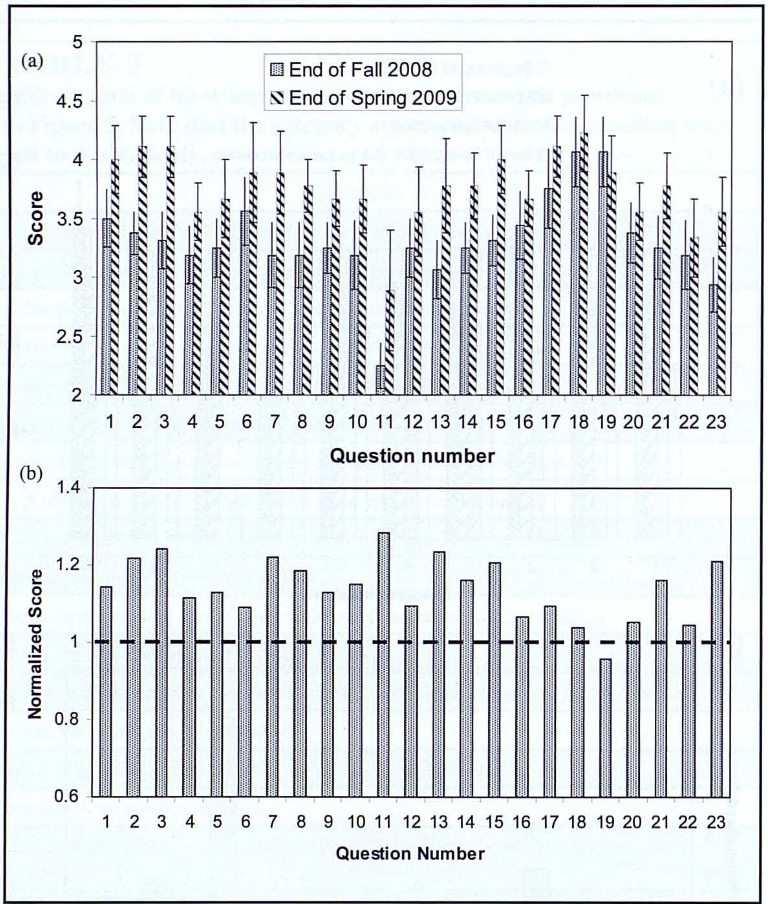


Figure 5. (a.) *Average scores for the survey on solving unstructured problems. Since no significant differences between the beginning and end of the fall semester were observed, only the survey results for the end of the fall semester are shown in this chart. The grading scale for these questions is 1 to 5. The questions are listed in Table 3.* ***(b.)*** *Score of each question at the end of the spring semester normalized to the beginning of the sequence.*

TABLE 4 Student comments taken from surveys and teaching evaluations and the end of the course sequence.	
Example comments:	• *Concepts covered in this class will be used in future research endeavors (9 votes out of 9)*
	• *Have been inspired to dig deeper into the concepts learned in this course sequence (9 votes out of 9)*
	• *The overall content of the class can be considered "Good" (5 votes) to "Very Good" (4 votes).*
	• *"I learned the most from the take home tests and presentations. These were excellent ways to understand the materials. But this was a great class! I learned a lot and am very glad to have taken it."*
Example recommendations:	• *"The instructors need to improve the integration of course materials to make it more concise and fluid, especially in Part I of the course. Make sure that the big picture is not lost."*
	• *"Part I of the course needs room for a learning curve on homework sets."*
	• *"A better integration of environmental and chemical concepts is needed. This could be achieved by a 'step-up' program, which provides a quick overview of the relevant concepts to build a common foundation for all, regardless of student initial background."*
	• *"Need to have more class resources (books, etc.). The textbook used in Part I should be replaced."*

provement, however. This net separation between the fall and spring can be explained by at least two factors. First, as stated above, most students enrolled in this course had very little to no prior knowledge of LCA. Second, this portion of the course was well-received by students for its integrative capacity, and the group projects allowed for interactive and hands-on activities that developed problem-solving skills.

D. Solving unstructured problems (Figure 5) – A total of 23 questions was asked about various aspects of working on unstructured problems in groups. The questions were asked at the beginning of the Fall 2008 semester and at the end of the fall and spring semesters. The questions are divided into various design attributes, as described by Safoutin, et al.[38] The questions are shown in Table 3 and the corresponding average scores graded on a 1 to 5 scale are shown in Figure 5a, where 1 = Poor, 2 = Fair, 3 = Good, 4 = Very good, and 5 = Excellent.

The results show no significant differences between the beginning and end of the fall semester (not shown). This might have been expected since the unstructured group activities were largely part of the Spring 2009 semester. Figure 5 shows comparative trends of students' scores with regard to their ability to adequately address various attributes of solving unstructured problems at the end of each of the two semesters. Overall, the students felt better prepared to handle unstructured problems at the end of the sequence (Spring 2009). As shown in Figure 5b, the largest improvements are observed in the need recognition (D2), problem definition (D3), information gathering (D7 – D8), modeling (D11), evaluation (D13), selection (D15), and implementation (D23) attributes. The smallest changes were observed in the documentation (D16), communication (D17 – D19), and iteration (D20, D22) processes, although the students were already confident in their ability to communicate. Interestingly, the students were clearly not confident with modeling a solution to a problem (D11) in the beginning. The students were more confident at the end of the sequence but this attribute of solving unstructured problems clearly remains lower than other attributes.

CONCLUDING REMARKS

The ultimate goal of this course development was to increase the awareness of engineering undergraduates to the life cycle stages of nanomaterials and of the importance of considering engineering design impact on the environment and public health during the design stage of processes and products incorporating nanotechnologies. The initial offering of the two courses led us to believe that our comprehensive approach to incorporating a life cycle assessment of nanotechnology into the engineering undergraduate curriculum has been well received by students. Table 4 shows some example comments and recommendations taken from the surveys and teaching evaluations during the spring semester. The students clearly enjoyed the topics covered in the course sequence. Students sometimes had difficulties making connections between the various parts of the course sequence, however. This sentiment is probably best reflected in the recommendation for a "step-up" program, which would provide tutorial sessions in areas where students had deficiencies in the course. For example, environmental engineering students would likely benefit from tutorials on transport, kinetics, and calculus while chemical engineering students may require sessions on analytical chemistry and biology. The instructors did find it difficult at times to balance the depth of the course material to the varied background of students from different disciplines. Therefore, we would recommend that a "step-up" program be included to establish better baseline knowledge for all students.

Further details on this course sequence, including slides for lectures, references to supplemental literature, and assignments, can be found at the course website, <http://www.che.ufl.edu/courses/SustainableNanotechnology/>.

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