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Nanotechnology Education—First Step in Implementing a Spiral Curriculum*

GANESH BALASUBRAMANIAN[1], VINOD K. LOHANI[2], ISHWAR K. PURI[1], SCOTT W. CASE[1] and ROOP L. MAHAJAN[3]

[1] Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. E-mail: bganesh@vt.edu

[2] Department of Engineering Education, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. E-mail: vlohani@vt.edu

[3] Department of Engineering Science and Mechanics, Department of Mechanical Engineering & Institute for Critical Technology and Applied Science, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. E-mail: mahajanr@vt.edu

A nanotechnology learning module was implemented into a freshman engineering course at Virginia Tech. The novelty of our approach is that an established spiral curriculum model has been employed, for the first time to the best of authors' knowledge, to design the nanotechnology option. The module was piloted in a freshman class (180 students) during spring '08. The key components included (1) a prior knowledge survey, (2) a 40-minute in-class presentation on basic nanotechnology concepts, (3) an activity that involves nanoscale image analysis and the plotting of molecular forces using LabVIEW software, and (4) a post-module survey. Lessons learned from the pilot implementation were incorporated appropriately to expose roughly 1450 freshmen to nanotechnology basics in fall 2008. The module was further refined in spring 2009 when pre- and post-tests were administered to assess the learning outcomes. Based on the prior knowledge data from about 1800 freshmen, we found that they had misconceptions about nanoscience fundamentals, e.g., regarding the (1) role of gravity at the nanoscale, and (2) behavior of intermolecular forces. Exit surveys revealed that approximately 18% of students had an interest in pursuing a nanotechnology option and approximately 65% believed that nanotechnology was relevant in their intended engineering majors. The LabVIEW provided an appropriate environment to implement the hands-on analysis of nanotechnology concepts, but we caution that such hands-on exercises should place greater emphasis on nanotechnology concepts than on LabVIEW skills.

Keywords: nanotechnology; freshman engineering; spiral curriculum

1. Introduction

One of the largest engineering programs in the United States is offered by Virginia Tech. A Department of Engineering Education (EngE; www.enge.vt.edu) was created within its College of Engineering (CoE) in early 2004 to improve engineering pedagogy and initiate engineering education research activities. EngE offers a common one-year General Engineering (GE) program for the initial preparation of approximately 1500 incoming engineering freshmen. Students transfer into fourteen ABET-accredited engineering majors after successfully completing the GE program. The EngE Faculty collaborates with other engineering departments and the School of Education to pursue engineering education research and curriculum development activities. A National Science Foundation (NSF) grant funded through its department level reform (DLR) program has been instrumental in introducing a spiral curriculum approach (briefly described in the following section), to reformulate the engineering curricula of bioprocess engineering and GE programs in the CoE [1].

Experiences in our DLR project were extended in 2008 to develop a nanotechnology option within the CoE Department of Engineering Science and Mechanics (ESM; www.esm.vt.edu) using this spiral curriculum approach. The effort is coordinated by nanotechnology and engineering education experts and is funded through the NSF Nanotechnology in Undergraduate Education (NUE) in Engineering program. The project makes use of the Nanoscale Characterization and Fabrication Laboratory (NCFL; www.ncfl.ictas.vt.edu) of the Institute for Critical Technology and Applied Science (ICTAS; www.ictas.vt.edu) at Virginia Tech.

The intent of this paper is to illustrate the implementation of a nanotechnology module for engineering freshmen in the context of a spiral curriculum, and assess the scope of teaching fundamentals of nanotechnology to a heterogeneous population of students in the freshman engineering class of Virginia Tech. We discuss the learning modules that are being implemented to establish the spiral theory-based nanotechnology option. Specifically, we provide implementation details of a freshman module that initiates the spiral frame-

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work. This module was successfully implemented in a freshman engineering course (Engineering Exploration EngE1024) in successive stages to roughly 180 students in the 2008 spring semester, 1450 students in the fall semester that year, and 180 students in the 2009 spring semester. An analysis of the assessment data to discuss the effectiveness of the module is also presented. We also discuss our plans for implementing the remaining components of the nanotechnology spiral.

1.1 Department-Level Reform (DLR) project (2004–2009)

This project is the first major curriculum reform and engineering education research project at Virginia Tech's College of Engineering and is funded by the US National Science Foundation. The twentieth-century psychologist, Jerome Bruner, proposed the concept of the spiral curriculum in his classic work *The Process of Education* [2] and *The Culture of Education* [3]. Bruner advocates that a curriculum as it develops should revisit basic ideas repeatedly, building upon them until the student has grasped the full formal apparatus that goes with them. This approach was adopted in a five-year (2004–2009) grant under a Department-Level Reform (DLR) program of the NSF (hereafter referred to as DLR project). In this project, a number of EngE faculty members collaborated with faculty from the Biological Systems Engineering (BSE) and the School of Education to reformulate the freshman engineering (also called general engineering) program within the EngE and the bioprocess program within the BSE department using a theme-based spiral curriculum approach [2–3].

Two major outcomes of this project were:

(1) spiral curriculum reformulation of bioprocess engineering within the BSE department;
(2) enhanced freshman engineering program.

The spiral reform process in bioprocess engineering included a seven-step process [4–5]. The DLR project investigators have conducted workshops within and outside the United States to share the details of the spiral curriculum development process [4]. Also, a number of hands-on activities have been implemented in EngE1024 to make it learner-friendly, contemporary and research-driven [6–7]. Some examples include:

(1) use of a clicker-based classroom response system to obtain student feedback [8];
(2) introduction to sustainability [9–10];
(3) ethics skits that enable engineering ethics learning [11];
(4) introduction of international research and education activities [12–13];
(5) use of the electronic portfolio (e-portfolio) for instruction [14–15];
(6) multi-disciplinary design based on mechatronics [16–17].

Tablet PC-based instruction was introduced in this course in 2006 [18–19]. A number of formative and summative assessment activities have been implemented in EngE 1024 as part of the DLR project to evaluate the learning experiences of freshmen [20–23]. Additional details are available in references [4, 24].

1.2 Literature review

Bruner's spiral curriculum theory has been adopted to reformulate diverse academic curricula. For example, Wark and Kohen [25] describe a spiral curriculum approach to redesign an hypnosis training program at University of Minnesota. Elizondo et al. [26] discuss the use of the approach in the horizontal and longitudinal integration of basic and clinical sciences to enable medical school curricular reform in Mexico. A core curriculum for medical education in the UK presented by Harden and Davis [27] uses the spiral approach as one of its underlying philosophies. Cowan et al. [28] advocate the use of the programming language Zeno in a spiral curriculum to facilitate problem-solving instruction in schools in Britain. The results of successful project-based spiral chemical engineering curriculum design, implementation, and evaluation at Worcester Polytechnic Institute are presented in a series of papers by Clark et al. [29], Dixon et al. [30], and DiBiasio et al. [31]. The authors claim that spiral-taught students displayed equal or better understanding of basic chemical engineering principles, performed better in upper level courses, and had higher satisfaction levels with their academic experience as compared to students who were taught traditionally through a compartmentalized sequence of courses. Gupta et al. [32] discussed an approach for transforming the educational experiences of transfer students in chemical engineering by developing and implementing a multidimensional spiral curriculum. Lohani et al. [33] have discussed the application of the spiral approach to reformulate the bioprocess engineering program in Virginia Tech.

A general approach to a bottom-up curriculum that retains the interdisciplinary nature of nanotechnology is to bring together faculty members from various departments who are able to incorporate the essential aspects of their different disciplines [34]. Bickle et al. [35] describe the implementation of a nanotechnology curriculum at University of Cincinnati through which second and third year students were exposed to the fundamental scientific concepts at the nanoscale, the related ethical issues, and hands-on laboratory experiences in nanoscale characterization and nanoparticle synthesis. Universities in Taiwan have provided opportunities to students from different majors in different years of their undergraduate education to learn through a common nanotechnology curriculum [36]. Another approach is to design the curriculum around applications [37]. Specifically designed courses have been developed to teach sophomores the fundamentals of nanotechnology and its potential to develop microarrays, micro-fluidics, and nanostructures [38]. Florida Tech implemented a freshmen fundamentals of nanotechnology course by teaching them about ferrofluid synthesis, quantum dots, and carbon nanotubes followed by hands-on experience of laboratory equipment, such as a Scanning Tunneling Microscope (STM) and an Atomic Force Microscope (AFM) [39]. Similar laboratory- based approaches with an emphasis on synthesis and characterization have been implemented elsewhere for engineering and science students [40–41]. Learning modules have been developed to integrate nanotechnology research into the undergraduate curriculum that help students understand the impact of sustainable engineering solutions in a global context [42]. Other examples include online nanotechnology programs [43] that rely on web-based distance learning, e.g., through the use of the LabVIEW software environment to understand a nanoscale experiment on a piezoelectric actuator [44]. Engaging freshman students to learn about nanotechnology has exposed them early on to a nanotechnology option [45–46]. Another approach has been to develop a nanotechnology concentration or major that does not require freshmen student exposure to nanotechnology [47]. The University of Wisconsin-Stout has developed a concentration available to Applied Science and Engineering Technology majors [48]. Nanotechnology is also taught from a humanities perspective through a discussion-based module that teaches students to understand the societal implications of the technology [49]. The possibility and utility of "sociotechnical integration" during nanoscale engineering research in an academic setting is reported in [50].

We have chosen to expose all engineering freshmen at Virginia Tech to some fundamental nanotechnology concepts through our spiral methodology to address student misconceptions, e.g. about the predominant intermolecular forces [51]. Students interested in pursuing a nanotechnology option are then provided with hands-on learning and advanced coursework in the experimental and computational aspects of nanotechnology, as well as relevant undergraduate research experiences.

1.3 Spiral curriculum approach

The concept of the spiral curriculum proposed by Bruner in *The Process of Education* [2] and *The Culture of Education* [3], was that learners—even beginners—could engage successfully with the central problems and questions inherent in any discipline *if* those key questions could be represented in a manner that invites real experimentation and inquiry at the appropriate level. One key to this idea is that the learning curriculum could be arranged so that the central questions, or themes in a discipline, would be returned to again and again as learners advance in their knowledge and intellectual capacity. The learning trajectory is thus represented as a spiral rather than the linear pathway that is characteristic of traditional schooling. As learners participate in increasingly complex investigations, organized carefully around the major themes of choice, they acquire in a more natural way the knowledge they need because it is connected to problems of real import and interest, and they acquire also the full intellectual apparatus associated with being the scientist, historian, or engineer rather than just learning about their chosen discipline. This approach was adopted to reformulate the bioprocess engineering curriculum within the Biological Systems Engineering (BSE) Department at Virginia Tech. Three spiraling themes, namely, design, systems, and ethics are considered in the spiral reformulation [4–5, 52].

We extended our experiences of implementing spiral theory based curriculum reformulation for structuring the nanotechnology option discussed in this paper. Nanotechnology is the scientific understanding of physical processes at the smallest scale of length and time that engineers can integrate into their systems. While both top-down and bottom-up approaches exist, the latter begins from the fundamentals of atoms and molecules, gradually inserting the complexities of nanostructures and nanoscale interfaces, and then moving on to understand how they contribute to microscale and macroscale systems. Considering the interdisciplinary nature of nanoscale science and engineering, and noting that new phenomena arise at the nanoscale, we believe that the spiral approach is the most effective way to impart and reinforce the basic concepts of nanotechnology. Implementation of nanotechnology education using an established learning theory model like the spiral approach has not been attempted to the best of our knowledge. While the bottom-up approach described by Lee et. al [34] considers the expertise of researchers from different disciplines, it does not provide a model for the actual curriculum. Other approaches are traditional lecture-workshop-demonstration schemes which follow the regular course structures, and not any theoretical model. The various learning experiences the students will undergo in pursuing our spiral theory based nanotechnology option are discussed in the next section.

1.4 Spiral experiences at different learning levels of the nanotechnology option

The implementation of the nanotechnology option includes learning modules designed to impart knowledge at four learning levels (i.e. Level 1 through Level 4). These modules are not necessarily courses that students must take during the freshman, sophomore, junior and senior years of their undergraduate engineering curriculum. Rather, the learning levels essentially imply the different stages of knowledge that students will gain through the spiral curriculum, with the content and complicacy of the learning experience gradually increasing from Level 1 through Level 4. Figure 1(a) shows the key concepts at the various learning levels of the nanotechnology option. For example, the knowledge students acquire about the role of intermolecular forces during the freshman nanotechnology module (Level 1) recurs when they learn about the computational techniques in molecular mechanics (Level 3). Likewise, the brief description of common experimental instruments used for nanoscale characterization provided during Level 1 is repeated in depth in Level 2, with hands-on experiences with the fabrication and experimental procedures. These learning experiences are revisited during the undergraduate research experience at Level 4 where, not only are the computational and experimental skills of the students acquired from the previous levels put to test, but the potential applications and ethical issues highlighted during the freshman nanotechnology module are also explored with greater emphasis. Details of the various learning objectives at the different levels of the nanotechnology option are listed in Table 1.

Table 1. Learning objectives of the spiral curriculum for the nanotechnology option

Level	Course/Experience	Learning Objectives
1	Nanotechnology module for freshmen (Implemented)	I. Differentiate between macro and nano, and demarcate the domain of nanotechnology amongst different length scales II. Describe the fundamental (intermolecular) forces significant at the nanoscale III. Identify existing and potential engineering applications of nanotechnology IV. Cite typical computational techniques and experimental instruments used in nanoscale research
2	Introduction to Nanoscale Characterization and Fabrication (Implemented)	I. Describe common methods for imaging nanometer-size features II. Describe common methods for manipulating features on this size scale III. Describe common spectroscopy methods IV. Explain the operating principle behind a nanotechnology instrument V. Identify an appropriate tool to solve a nanotechnology problem
3	Introduction to Computational Molecular Mechanics (Being Developed)	I. Describe the role of different intermolecular forces at the nanoscale II. Explain the physics and mathematics behind molecular dynamics simulation technique III. Construct simple molecular geometries of nanoscale systems and devices IV. Conduct basic numerical experiments using pre-existing computational codes V. Conduct literature review to be aware of the present scenario on a chosen research topic in nanotechnology VI. Prepare a report summarizing important conclusions of the project undertaken during the course
4	Undergraduate Research (Implemented)	I. Conduct a literature review on a current research topic II. Work in conjunction with a faculty advisor to develop an independent research plan for the topic III. Explain the importance of ethical research conduct IV. Demonstrate proper practices in research documentation and data collection V. Conduct atomistic simulations of the nanoscale system specific to the research VI. Fabricate the experimental sample and characterize the same using appropriate techniques VII. Prepare a report and/or presentation appropriate to the project summarizing important conclusions

The key learning activities at various learning levels in the nanotechnology option are presented in Figure 1(b). As an example, the Level 1 hands-on exercises involving the determination of diameter of carbon nanotubes and plotting the nature of intermolecular forces provide students with fundamental notions about nanostructures, which recur at the higher learning levels. Students watch videos of nanotechnology experimental instruments such as an Atomic Force Microscope and a Scanning Electron Microscope, during Level 1 and then use this equipment to participate in hands-on exercises for nanoscale characterization at Level 2. Similarly, the generic ideas obtained from the Level 1 plotting exercise of intermolecular forces is discussed in greater detail at Level 3 when students acquire further knowledge about molecular forces and their influence on properties at the nanoscale, and familiarize themselves with computational codes that include the potential models necessary to simulate the systems. These learning experiences again spiral into Level 4, when students take up independent research projects that involve both the experimental skills and simulation expertise imparted during the previous levels of the curriculum.

In order to further highlight the spiral theory concepts, a visual representation of the key learning experiences of the students at the four distinct learning levels of the nanotechnology option is shown in Figure 1(c). Level 1 indicates the fundamental ideas about the realm of nanotechnology to increase students' awareness and acquaintance to nanoscale systems and their potential applications. In Level 2, details about experimental characterization of nanoscale devices with hands-on sessions are provided to increase their skills with instruments like a Scanning Electron Microscope (shown in the figure), an Atomic Force Microscope, a Transmission Electron Microscope, etc., which the students can employ for specific research problems. Level 3 includes modeling of nanoscale physical phenomena through atomistic simulations where the origin of intermolecular forces and their influence on system behavior are analyzed with the aid of molecular dynamics simulations. Students' spiraling experiences conclude with an undergraduate research project on a current research area in nanotechnology at Level 4 of the learning spiral. An example research project is to determine effects of chirality on the thermal conductance of carbon nanotubes. While students learn what carbon nanotubes are in Level 1, the characterization skill acquired in Level 2 enables them to visualize the chirality of carbon nanotubes in a sample. The computational ability obtained from Level 3 equips them to investigate the influence of chirality on the thermal conductance of carbon nanotubes.

At the time of writing, the activities at Level 1 are included as a learning module in a freshman course, details of which are discussed in the following sections. The Level 2 activity is implemented in the form of a complete course that was offered for the

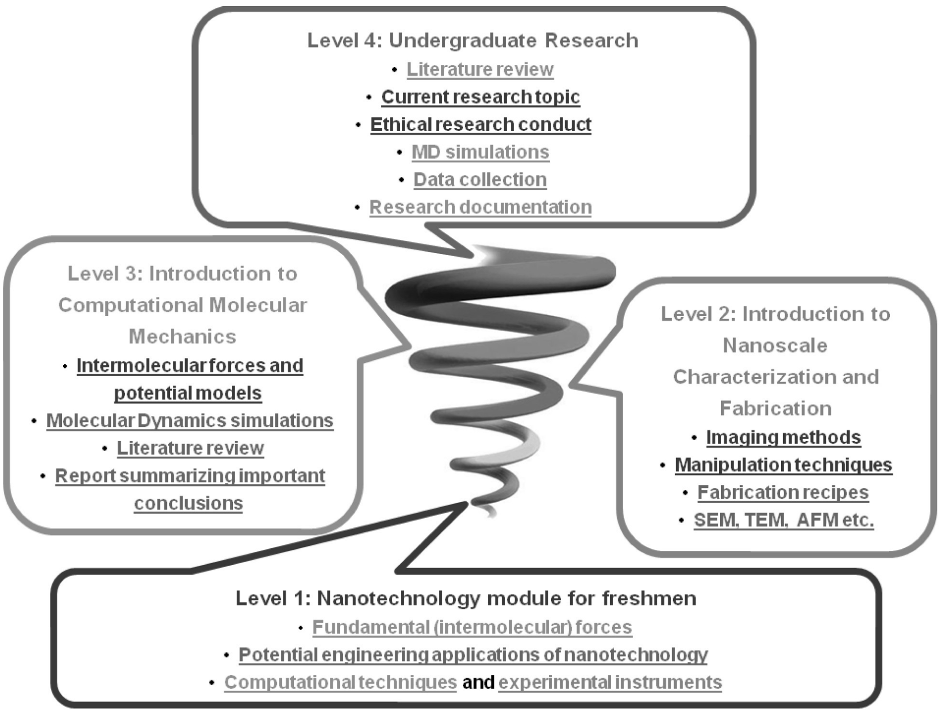


Fig. 1 (a). Nanotechnology option developed using the spiral curriculum approach.

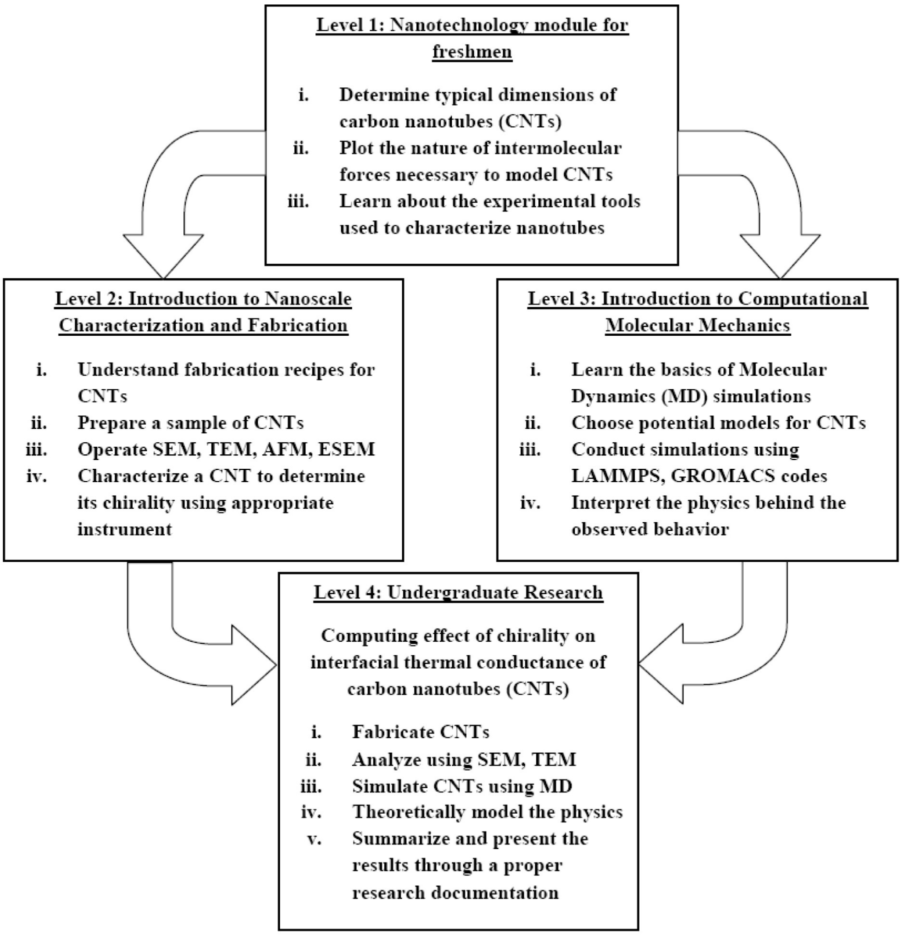


Fig. 1 (b). Knowledge areas including examples of hands-on activities and their relevance in the spiral theory-based nanotechnology option.

first time in spring 2010. The Level 3 activity will be part of a course that is under development. Students have participated in nanotechnology related undergraduate research activities under the mentorship of faculty and senior graduate students in the ESM department. However, the recruitment of students to participate in the proposed nanotechnology option is ongoing at this time.

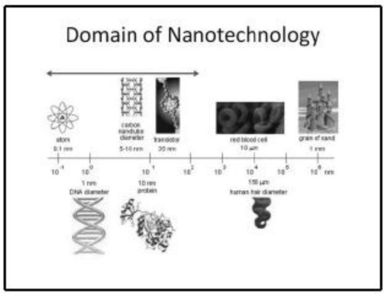
1.5 Nanotechnology option within the ESM department

ESM has 25 faculty members and about 130 undergraduate students from the sophomore to senior levels. The relatively small undergraduate program size makes it an excellent site to examine the effectiveness of instructional approaches, such as the nanotechnology option described in this paper. As shown in Figure 1(a), all engineering freshmen are introduced to basic nanotechnology fundamentals regardless of their final major through our approach to initiate the spiral curriculum. In addition to repeating basic nanotechnology concepts in the ESM nanotechnology option, their learning experiences will focus on nanoscale material characterization and computational molecular mechanics. Students will also be expected to conduct a nanotechnology-related research project mentored by CoE faculty members and the graduate students under their supervision. Table 2 provides details of the various courses and their contents.

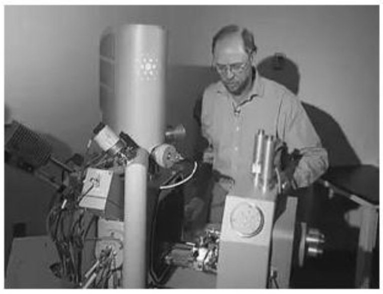
1.6 Freshman engineering nanotechnology module

All Virginia Tech engineering freshmen are required to take a two-credit *Engineering Exploration* (EngE 1024) course during their first semester of enrollment in the GE program, which is the only common engineering course that all undergraduates take. The course focuses primarily on developing problem solving, critical thinking, and engineering design skills. The delivery format includes a fifty minute lecture followed by a ninety minute hands-on workshop every week.

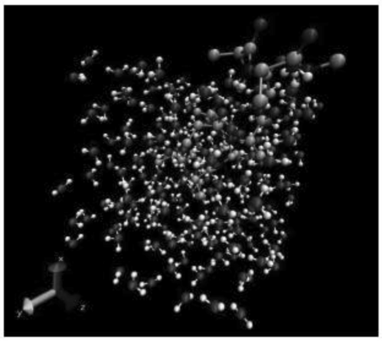
The DLR project investigators have collected demographic data to describe the participants who have participated in various activities implemented as part of DLR project [23]. Majority of students



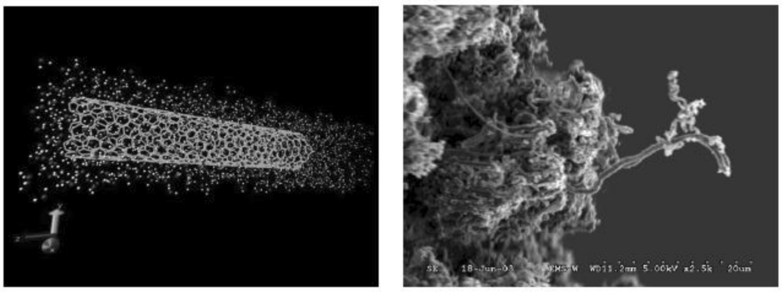
Level 1: Basics of nanotechnology



Level 2: Nanoscale characterization experiment with SEM



Level 3: Nanoscale computations using molecular dynamics simulations



Level 4: Investigation of thermal conductance of carbon nanotubes using molecular simulations (left) and the corresponding experimental characterization (right) using SEM

Fig. 1 (c). Visual representation of the different levels of the spiral curriculum.

Table 2. Summary of the various learning modules of the spiral curriculum approach

Course/Experience	Proposed contents	Implementation plan
Nanotechnology module for freshmen	Prior knowledge survey; pre-test, nanotechnology lecture and video presentation; nanotechnology experiment video; hands-on activity using LabVIEW-based analysis; post-test	Implemented in Spring ’08, Fall ’08, and Spring ’09 in EngE
Introduction to Nanoscale Characterization and Fabrication	Describe common methods for imaging and manipulating nanometer-size features; common spectroscopy methods; explain operating principle of nanotechnology instruments; identify appropriate tool to solve a nanotechnology problem	Implemented using NCFL equipment and ICTAS instructors in Spring ’10
Introduction to computational molecular mechanics	Introduction to statistical mechanics and statistical thermodynamics; Newtonian dynamics for particle systems; soft and hard sphere models; stochastic and deterministic methods; parallel computing and algorithms	Being developed
Undergraduate research	Nanotechnology-based experimental, theoretical and computational research experiences	Implemented in ESM and ICTAS

who participated in this study are engineering freshman at Virginia Tech's College of Engineering. Based on analysis of data of two engineering classes (i.e., class of 2008 and 2009) it is observed that the majority of the freshman engineering class is male (85%) and white (80%). In regards to prior background experiences, approximately 50% of the class has an engineer in the family and also has prior programming experience. In addition, the majority of students (75%) did not take any pre-engineering courses in high school. A survey was designed to ask students to indicate all of the engineering majors they were interested in, and students selected mechanical engineering (53%), followed by aerospace and ocean engineering (40%), electrical or computer engineering (37%) and civil or environmental engineering (33%). It may be noted that students were allowed to select multiple possible majors in this survey [23].

One of the learning objectives of EngE1024 is that students will be able to demonstrate a basic awareness of contemporary global issues and emerging technologies, and their impact on engineering practice after successful completion of the course. The nanotechnology module discussed in this paper meets this objective. The nanotechnology learning module was piloted in EngE 1024 in the 2008 spring semester for approximately 180 students [55]. Student feedback was used to enhance the module that was again implemented in the entire freshman class of about 1450 in the 2008 fall semester, and with further revisions in the 2009 spring semester to about 180 students. Therefore, approximately 1800 students have participated in learning basic nanotechnology concepts using this module. The following sections discuss the development, implementation, and assessment of the module, and include assessment questions and web links to instructional videos that will enable interested educators to learn from it and also implement it.

2. Development of freshman level nanotechnology learning module

2.1 Spring 2008 pilot

Approximately 180 students enrolled in EngE 1024 in the 2008 spring semester. The nanotechnology module was piloted for the first time in this course. It included four components:

(1) prior knowledge survey;
(2) in-class presentation;
(3) hands-on nanotechnology activities;
(4) post-module survey.

2.1.1 Prior knowledge survey

In order to assess students' prior knowledge of nanotechnology, we developed a short survey of ten questions that are listed in Appendix A (question numbers 1–10). The survey was implemented two weeks before the classroom instruction and hands-on activities took place. Figure 2 presents student responses to select survey questions. About 73% knew the definition of a nanometer but roughly 43% thought that the gravitational force played a dominant role at the nanoscale. Most students did not understand the behavior of intermolecular attraction as molecules move apart, and the repulsive forces when they move closer to each other. Most freshmen were incorrect by an order of magnitude when asked to identify the size of an atom. A majority thought that the most important application of nanotechnology was in the medical sciences. Although only 5% students reported prior exposure to basic nanotechnology concepts, 60% expressed an interest in learning about nanotechnology. These results were used to design an in-class-presentation followed by a set of hands-on activities.

2.1.2 In-class presentation

A nanotechnology expert (the third author) developed this presentation in consultation with the other authors in two formats, i.e., as presentation slides and an online video. Figure 3 presents some of the slides for the sake of illustration. The topics covered in the presentation are summarized in Table 4 of Section 3. These topics included, a background of nanotechnology development, the interdisciplinary nature of the subject involving physics, chemistry, biology and engineering disciplines, a comparison of the dominant forces at the macro- and nanoscales to help students to clear their misconceptions about the behavior of intermolecular and gravitational forces, nanostructures observed in nature, areas of applications with examples varying from novel electronic and semiconductor devices to nanoparticles present in everyday applications like paints, and finally the societal and ethical issues associated with the technology. We have provided online links to this freshman module in Section 3 to enable access for the interested reader.

We took advantage of the classroom technology (i.e., Tablet PCs and DyKnow software) available to educators within the College of Engineering for developing interactive in-class presentations. Engineering freshmen at Virginia Tech are required to have a Tablet PC. The second author has developed and implemented technology enhanced classroom pedagogy using TabletPC and DyKnow technologies [19, 53, 55]. These technologies were used during the nanotechnology presentation to develop an interactive learning environment. For example, in order to explain significance of various forces acting at the nanoscale, students were first asked to

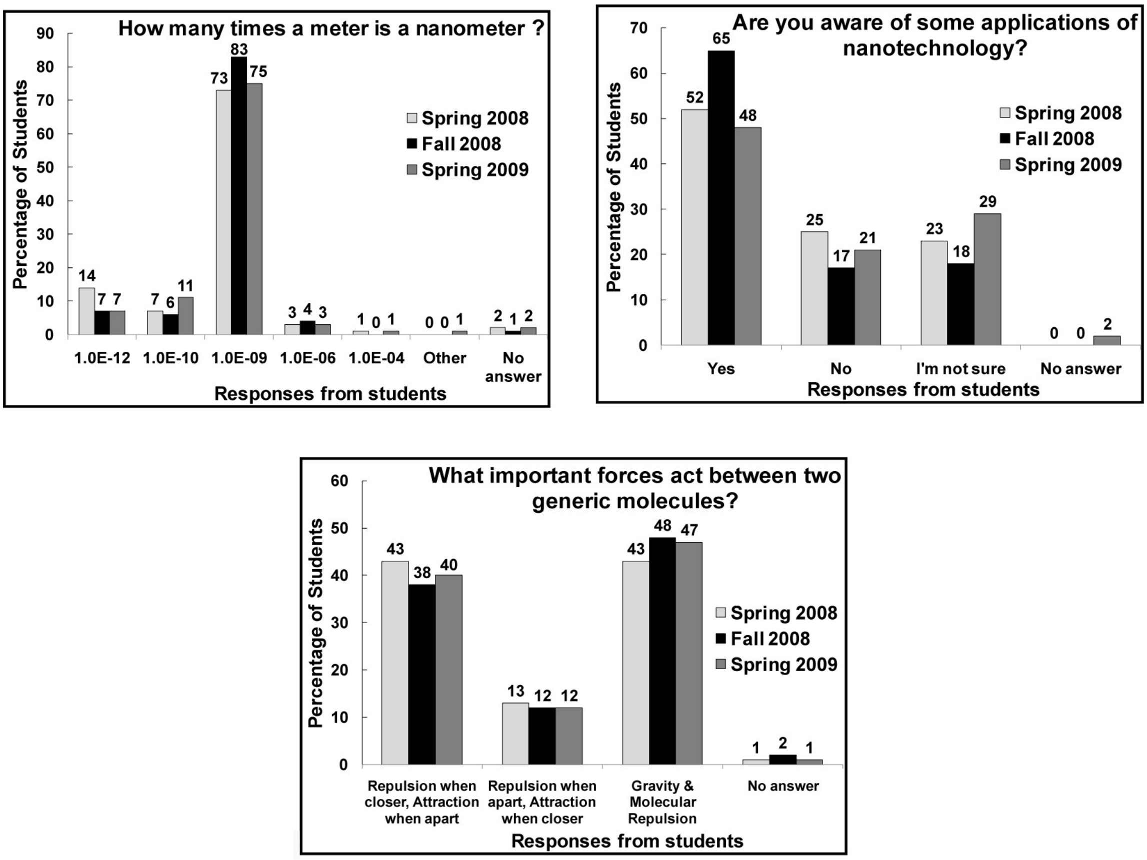


Fig. 2. Student responses to some questions in the prior knowledge survey (Spring ’08, N=99; Fall ’08, N=868; Spring ’09, N=149).

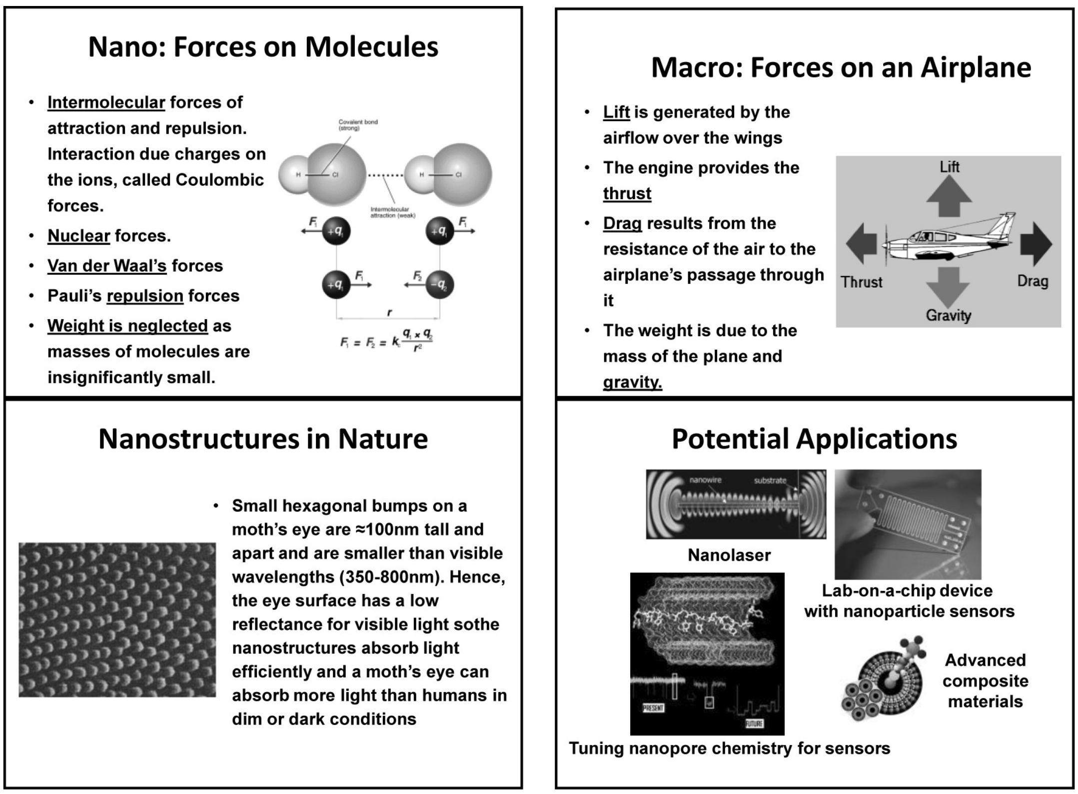


Fig. 3. Slides from the in-class presentation.

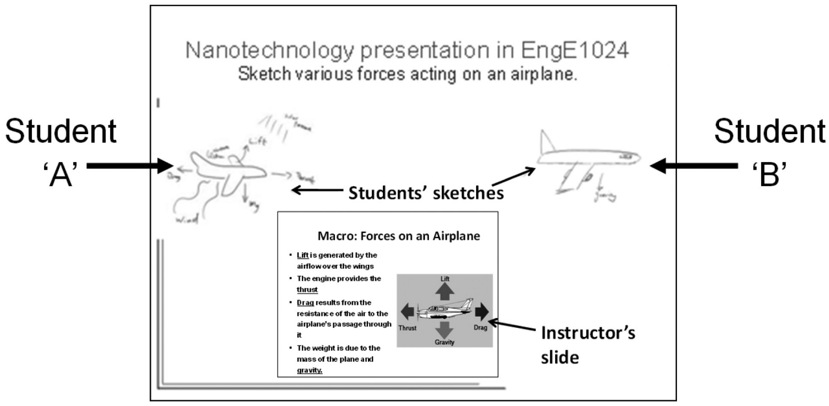


Fig. 4. Example of feedback-based classroom instruction.

think about the dominant forces acting at the macroscale. They were assigned a short in-class exercise that involved sketching the various forces acting on an airplane (see Figure 4). Student sketches were collected anonymously using the TabletPC and DyKnow technologies. As shown in the figure, student 'A' was able to describe the different forces while student 'B' only considered gravity. Anonymously retrieved student sketches were displayed to the class shortly after they were retrieved to illustrate deficiencies. Thereafter, the instructor's slide that depicted the correct macroscale forces, also shown in Figure 4, was discussed.

2.1.3 Hands-on activity workshop

Students learn LabVIEW programming in EngE 1024 [56]; thus we decided to use LabVIEW environment to introduce nanotechnology concepts. Keeping in mind the student misconceptions observed from the prior knowledge survey and academic preparation of students, three nanotechnology hands-on exercises were developed in a LabVIEW environment:

(1) measurements of the typical dimensions of carbon nanotubes;
(2) introduction to the Lennard-Jones potential function and its graphical analysis;
(3) analysis of the gravitational force between two molecular masses.

Students were provided with carbon nanotube images and used the LabVIEW VISION toolkit to measure their dimensions as illustrated in Fig. 5(a). In a second exercise, students were introduced to the Lennard-Jones potential function which is used to model intermolecular interactions. The students plotted the force derived from this function and analyzed the interaction forces between two molecules. These showed that increasing separation enhances intermolecular attraction while repulsive forces are strengthened as the two molecules come closer, as shown in Fig. 5(b). Finally, students plotted the gravitational force as a function of

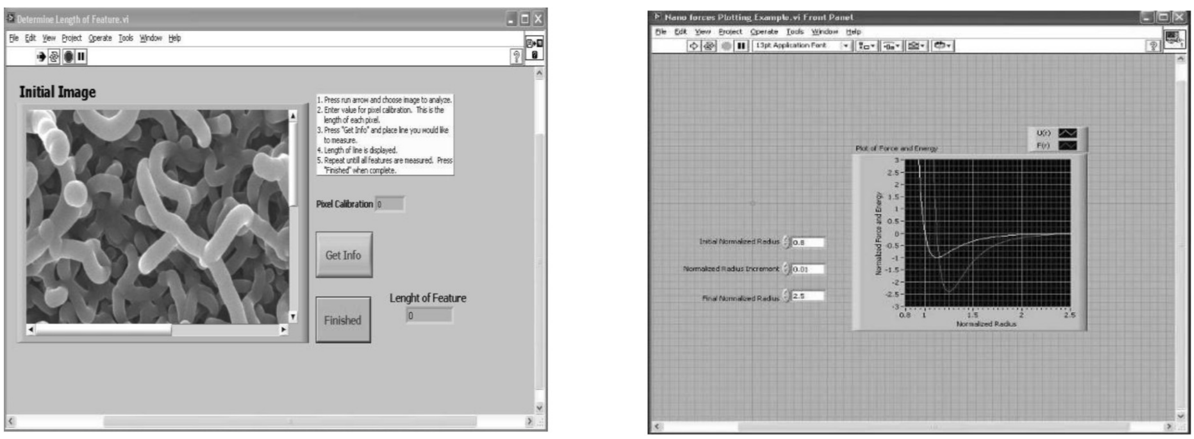


Fig. 5. Hands-on analysis using the LabVIEW environment. (a) Determination of diameter of a carbon nanotube, and (b) plots of the Lennard-Jones potential and the force between two atoms.

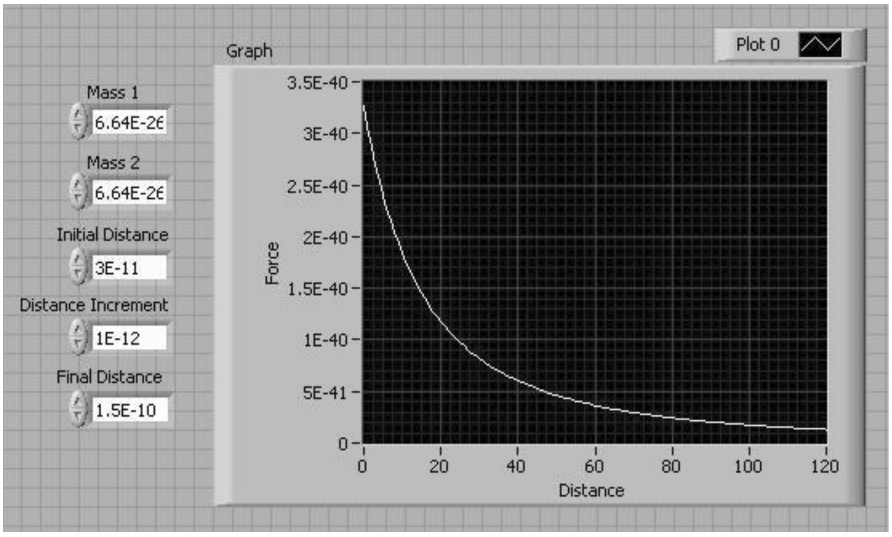


Fig. 5. (c) Gravitational force of attraction (in Newton) between two atoms separated by a certain distance (in meters) shows that not only is the force monotonic in nature but also that the magnitude of the attraction is negligible in comparison to the molecular forces present between atoms.

separation distance between two molecular masses. This exercise emphasized that gravitational forces are insignificant at the nanoscale due to the negligibly small molecular masses (see Fig. 5(c)).

2.1.4 Post-module survey

As part of the assessment activities for EngE 1024, a student exit survey has been implemented since the 2004 fall semester [22]. Additional questions related to nanotechnology learning experiences were added to this survey, as follows:

(1) Please recall (instructor's name)'s video presentation and workshop activities on nanotechnology this semester. These activities motivated me to pursue a nanotechnology minor/option; Strongly Agree/Agree/No Opinion/Disagree/ Strongly Disagree;
(2) Do you see the relevance of nanotechnology in your intended major of engineering? Yes/No/I have not decided a major yet;
(3) Please comment on your overall experiences of learning about nanotechnology and provide suggestions for future improvement. (Free response).

Student responses were collected at the end of 2008 spring and fall, and 2009 spring semesters for which the results are discussed in Section 4.

2.2 Fall 2008 implementation

In the 2008 fall semester, approximately 1450 freshmen enrolled in EngE 1024. They were divided into eight large lecture sections that were further divided into 49 hands-on workshop sections. The lecture sections were taught by faculty members while graduate teaching assistants (GTAs) taught the workshop sections. All GTAs underwent two-week training on the basics of nanotechnology. This training covered fundamental principles of molecular interactions, the forces involved, and description of a simple potential model, Lennard-Jones potential, the relevance of the attractive and the repulsive terms, the insignificance of gravitational force at the nanoscale, discussion on the increase in surface area to volume ratio, and its effects on material properties. The experiences gained during the 2008 spring semester were incorporated to implement changes into the nanotechnology learning module when it was taught in the 2008 fall semester. The module included:

(1) prior knowledge survey;
(2) forty minute nanotechnology video assigned as a homework assignment,
(3) in-class question and answer session facilitated by the Tablet PC and DyKnow technologies;
(4) hands-on activities;
(5) video presentation on a nanotechnology experiment;
(6) homework assignments on nanotechnology concepts;
(7) post-module survey.

2.2.1 Prior knowledge survey

The 2008 spring semester prior knowledge survey (question numbers 1–10 in Appendix A) was again implemented in the entire freshman class on a voluntary basis and more than 50% students responded (Fig. 2). Student responses again revealed the same misconceptions as during the 2008 spring semester pilot.

2.2.2 *Nanotechnology video presentation*

Students were again provided with an introduction to nanotechnology concepts through an online video and a slide presentation. It consisted of the same key topics discussed during the 2008 spring semester implementation of the module. Students were allowed one week to review a forty minute nanotechnology video developed by the nanotechnology expert and were instructed to come prepared to class to answer and ask questions on the various concepts presented in this video. For details and online links to the video, please see Section 3.

2.2.3 *In-class question and answer sessions*

Three Ph.D. students from ESM with nanotechnology research expertise assisted the EngE 1024 faculty instructors during in-class question and answer sessions on the nanotechnology concepts discussed in the video. Tablet PC and DyKnow technologies were used to obtain student responses to the following three questions:

(1) List the forces that dominate intermolecular interactions.
(2) List two engineering applications of nanotechnology discussed in this presentation. Can you also share example of an application that was not discussed in this presentation?
(3) Suppose you are invited to your high school to give a short talk on your first year experiences at this university and you decided to say one thing about nanotechnology in this talk. What will you say?

Students were given about two minutes to provide written responses that were retrieved by instructors anonymously using TabletPC and DyKnow technologies. The ESM graduate students reacted to student feedback. Figure 6 lists some responses from students. That gravity is not a significant force at the nanoscale was explained to them. In response to the second question, students listed applications related to bio-nanotechnology, space elevators and microchips. Most students considered nanotechnology to be a significant emerging area for scientific research and predicted major development in the medical sciences. Some provided critical opinions

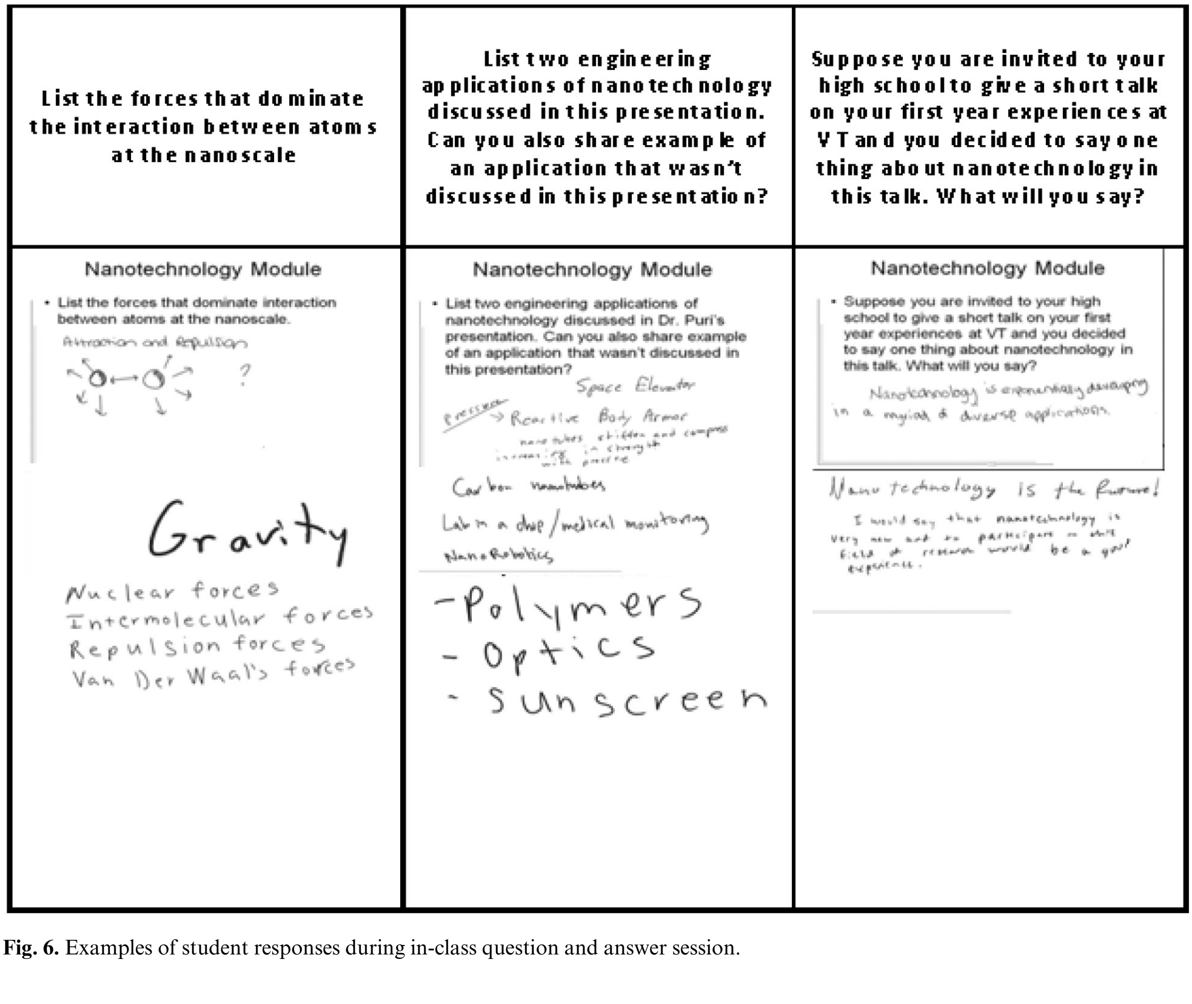


Fig. 6. Examples of student responses during in-class question and answer session.

Table 3. Comparison of surface area to volume ratio between a nanotube and a PVC pipe

Dimension	Carbon Nanotube	PVC Pipe
Diameter	24.39 nm = 24.39×10^{-9} m	5×10^{-3} m
Surface area	7.66×10^{-13} m^2	1.57 m^2
Volume	4.67×10^{-21} m^3	1.96×10^{-3} m^3
Surface area/Volume	1.64×10^{8} m^{-1}	8×10^{2} m^{-1}

about the negative aspects of such powerful technologies, with their imaginations suggesting the birth of "nano-babies" using DNA-mediated interactions, to producing "nano-weapons" and using destructive novel high energy physics applications.

2.2.4 Hands-on activities

The LabVIEW environment was again used to repeat the hands-on analysis activities of the 2008 spring semester pilot. However, in order to provide further insight into the dimensions of carbon nanotubes, a new exercise was developed that compared surface area to volume ratio of a nanotube with that of a large PVC plumbing pipe. Students were asked to measure the diameter and length of a typical nanotube using the VISION Toolkit in LabVIEW and to calculate the ratio. They were also provided with the dimensions of a typical PVC plumbing pipe and asked to compare its ratio with that of the nanotube. Table 3 summarizes the typical values that students obtained. This exercise demonstrated the significant increase in the surface area to volume ratio at the nanoscale that can be favorable for biochemical, and heat and mass transfer applications. The exercise complemented the discussion of this topic in the video presentation and emphasized nanotechnology concepts more than the LabVIEW concepts.

2.2.5 Nanotechnology experiment video

In response to student feedback during the 2008 spring semester pilot, a video demonstrating a basic nanotechnology experiment was developed at the NCFL. Students were assigned to watch which this seven minute video demonstrated a nanotechnology experiment using a Scanning Electron Microscopy (SEM) to capture high resolution magnified images of a human hair and of carbon nanotubes. An SEM expert briefly explained the techniques involved in the preparation of the samples and the salient features and capabilities of the instrument. The large size of our freshman engineering class and high cost of nanotechnology experiment equipment were the main reasons we decided to use an experimental video instead of asking students to participate in the experiment. Please see Section 3 for more details and online links.

2.2.6 Post-module survey

Questions added to the EngE 1024 exit survey in the 2008 spring semester pilot were asked of all freshmen at the end of the 2008 fall semester. About 314 students responded. These responses are summarized in Fig. 8(a) and 8(b). Students felt that the video presentation was too long and incorporated a variety of complex nanotechnology concepts. They indicated their preference for a shorter video that covered a few major fundamental concepts but contained greater discussion of applications. Many students, especially those who did not plan to further study nanotechnology as part of their curriculum, found the detailed discussion of the concepts covered in the video to be difficult to understand. Most students still thought that the hands-on analysis placed greater emphasis on LabVIEW skills rather than a real-time demonstration of nanoscale activity.

2.3 Spring 2009 module

The 2008 fall semester module was modified further to address student concerns. A revised module was implemented in EngE 1024 for about 180 freshmen during the 2009 spring semester. Instead of the prior knowledge and post-module surveys, the students were asked to voluntarily participate in a pre- and a post-test. The prior knowledge survey implemented during the previous two semesters was modified appropriately to develop the test questions. A shortened twenty minute version of the video presentation was created. The 2009 spring semester implementation included:

(1) pre-test;
(2) nanotechnology videos and slides assigned as a homework assignment;
(3) nanotechnology experiment video as a homework assignment;
(4) in-class question and answer session assisted by Tablet PC and DyKnow technologies;
(5) hands-on analysis activities;
(6) post-test.

2.4 Pre-test

Over 80% of students voluntarily participated in the pre-test which contained twelve questions (Appen-

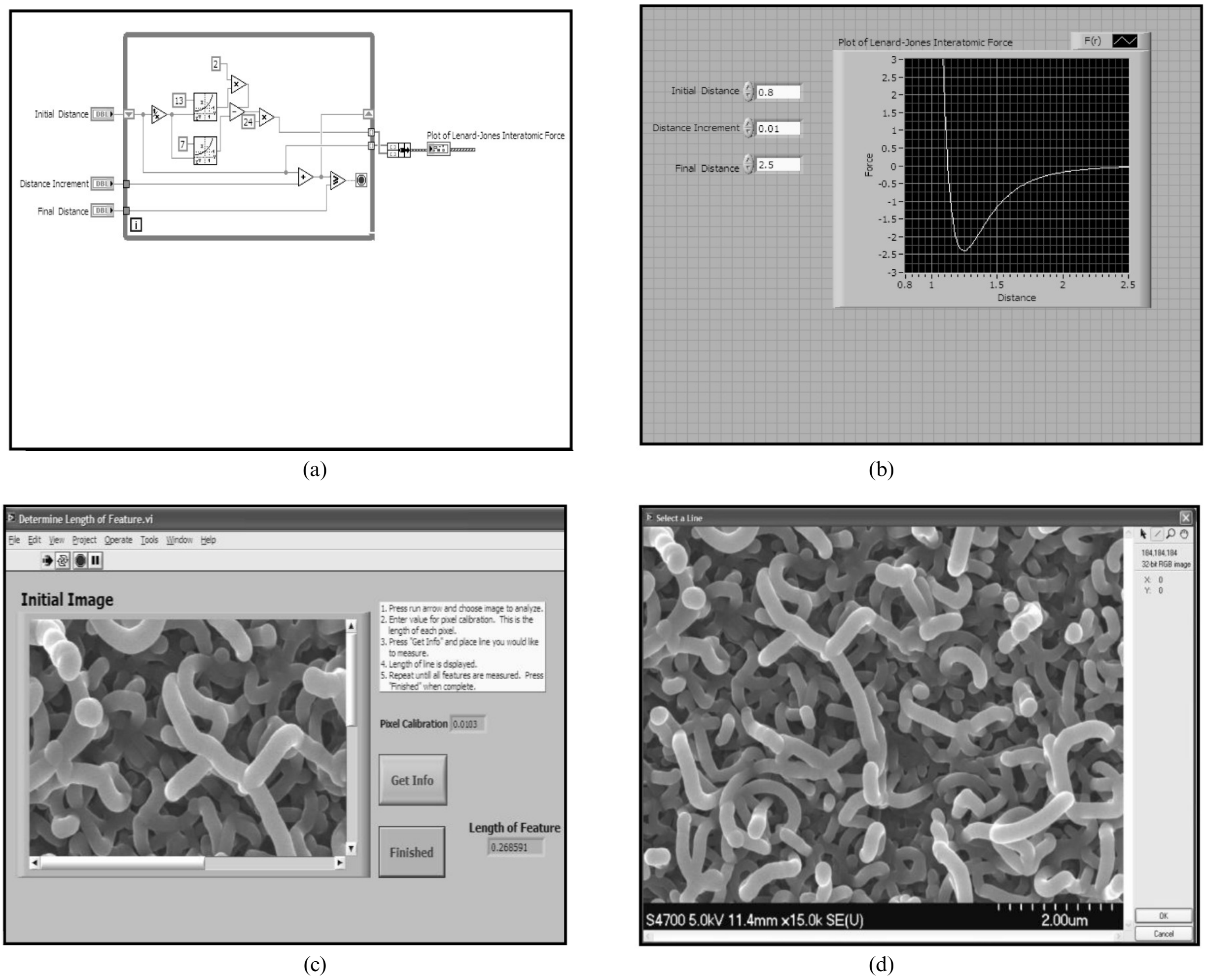


Fig. 7. LabVIEW activities developed for hands-on exercises involving plotting of Lennard-Jones interatomic force. (a) represents the LabVIEW block diagram and (b) shows the front panel showing the attractive (negative) and repulsive (positive) natures of the interaction force between two atoms with respect to the separation distance between them; (c) and (d) represent the exercise using LabVIEW VISION toolkit used by students to calculate the dimension (diameter, length) of a carbon nanotube.

dix A), i.e., all questions that were asked of the students through the prior knowledge survey in the 2008 spring and fall semesters (numbers 1–10 in Appendix A) with two additional questions (numbers 11–12 in Appendix A). Again, the pre-test results indicated that students were unclear about the role of gravity at the nanoscale (as shown in Section 4, Fig. 9).

2.4.1 Nanotechnology video presentation

Students were allowed a week to review a twenty minute nanotechnology video and the corresponding slides. The link to the longer version of the nanotechnology video, developed for the 2008 fall semester was provided as an optional activity.

2.4.2 Post-test

After completion of all nanotechnology instruction, students were asked to complete a post-test survey. There was significant improvement in the previously noted student misconceptions (shown in Section 4, Fig. 9). However, notably, after the completion of the module about 18% of the students still believed that gravity was dominant at the nanoscale.

3. Nanotechnology module for freshman engineering students

In this section, we provide details of the components of the freshman nanotechnology learning module that should enable an educator to implement the module.

3.1 Pre-and post-test questions

This multiple choice test is presented in Appendix A. An online link to this test was created and students were requested to complete it on a voluntary basis before the instruction occurred. We made it very clear that student scores on this test would not

Table 4. Key concepts discussed in the nanotechnology presentation

Key topics included in the presentation on nanotechnology
• Brief history of the subject • Domain of nanotechnology amongst different length scales • Interdisciplinary aspects • Comparison of macroscale and molecular forces • Molecular mechanics • Material behavior at the nanoscale • Nanostructures in nature • Applications: Everyday uses, electronics, nano-biotechnology etc. • Ethical issues

Table 5. Salient features of nanoscale characterization experiment using SEM

Key topics demonstrated in the nanotechnology experiment
• Facilities at the NCFL, ICTAS, Virginia Tech • Capabilities and uses of Scanning Electron Microscopy (SEM) • Applications of different nanoscale materials • Sample preparation and mounting • Image analysis and appropriate magnification for carbon nanotubes and human hair test samples • Measurement of typical dimensions • Phase determination using EDS spectra for other samples

influence their course grades. The same test was administered as a post-test once all instructional activities were completed.

3.2 Nanotechnology video presentation and slides

Table 4 summarizes the key topics included in the nanotechnology video and slides.

The video and slides can be viewed at http://www.vbs.vt.edu/content/adhoc/fall2008/Puri_Nanotech/

Students accessed above instruction materials from Blackboard sites. While the authors have not recorded data on frequency of students' accessing these materials, another study of one of the authors, indicates that use of classroom technology (such as Blackboard, TabletPCs, and DyKnow) have been effective in developing a feedback-based learning environment in the classroom [53].

3.3 Nanotechnology experiment video

A nanotechnology characterization experiment on carbon nanotube and human hair samples was analyzed with an SEM at the NCFL. The salient points of this video are presented in Table 5.

The video is available at http//light.vbs.vt.edu/adhoc/fall2008/ICTAS08.mov

It may be mentioned that the videos discussed above were professionally done with the support of the Virginia Tech Video/Broadcast Services (VBS).

3.4 Hands-on workshop activities

The LabVIEW environment was used to develop and implement hands-on activities for the nanotechnology module. Figures 7(a)–7(d) show images of the LabVIEW Virtual Instruments (VIs) created to plot the attractive and repulsive forces due to the Lennard-Jones potential between two interacting molecules, and measurements of typical carbon nanotube dimensions using the VISION toolkit of LabVIEW.

The basic concepts involved in the LabVIEW VIs are applications of different data types, use of built-in functions like add, multiply, subtract and power, incorporating a while loop structure and the knowledge of shift registers. Before implementing the nanotechnology module, students learned these LabVIEW concepts as part of programming instruction in EngE 1024. Instructions for implementing this hands-on exercise are:

- Cover the fundamentals of LabVIEW programming (i.e., data types, control structures, and plotting concepts).
- Have students install the VISION toolkit which is an add-on to the LabVIEW.
- Provide students with carbon nanotube image files and the supporting LabVIEW VIs for image analysis and plotting. The files can be accessed at https://filebox.vt.edu/users/bganesh/NUE:%20Spiral%20Approach/ *Username*: filebox.nue, *password*: lohani
- Explain the Lennard Jones (L-J) potential and force expressions, the role played by the material parameters, and discuss the attractive and the repulsive terms.
- In-class work (Total time of sixty minutes distributed equally to three different activities):
  (a) Determination of size (20 minutes): Calculate the length and diameter of a typical carbon nanotube. The exercise involves a briefing of

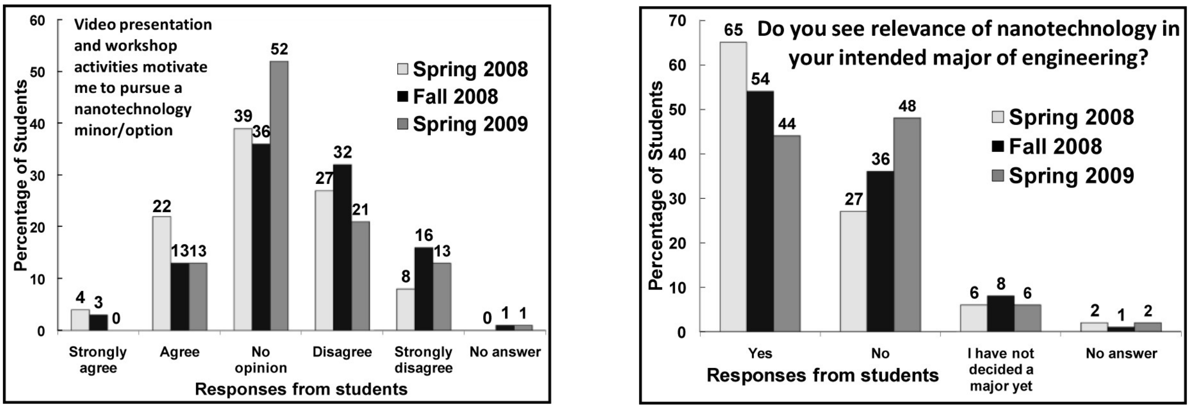


Fig. 8. Student responses to post-module survey (Spring ’08, N=49; Fall ’08, N=314; Spring ’09, N=66).

the concepts of pixel calibration in order to convert the measured dimension from pixels to corresponding length units, e.g., in micrometers or nanometers.

(b) Plot the L-J force function (20 minutes): Using the basics of LabVIEW programming to graph the L-J force expression with the values for material parameters provided to the students by the instructor. The exercise involves locating the value for the interatomic separation distance for which this force becomes zero, positive, and negative.

(c) Calculate the surface area to volume ratio of a typical carbon nanotube and compare it with that for a standard PVC pipe (20 minutes): The dimensions for the PVC pipe and the formulae for obtaining the surface area to volume ratio are provided to students beforehand, while carbon nanotube diameter and length are computed by students using LabVIEW and a given image. The purpose of this activity is to show the marked difference in geometric characteristics that arises from the large surface areas of the nanostructures in comparison to their macroscale counterparts. Also, this activity laid more emphasis on nanotechnology concepts (e.g., high surface area to volume ratio) as opposed to LabVIEW concepts.

4. Assessment

We now summarize student responses to the exit survey, and pre- and post-test questions on a semester-wise basis. Two key instruction-related inputs from students in 2008 spring semester were:

(1) hands-on activities should emphasize nanotechnology concepts over LabVIEW concepts;
(2) students expressed their desire to observe an actual nanotechnology experiment in order to develop a better understanding and appreciation for this emerging technology.

Regarding the in-class presentation, many students felt that too much fundamental material was covered in a single lecture and suggested that nanotechnology applications be equally emphasized. A majority thought that nanotechnology was relevant to their majors with about 18% showing interest in pursuing a minor or option in nanotechnology.

Students taking the class during its 2008 fall semester implementation felt that the video presentation on nanotechnology was too long and also suggested that a shorter presentation be prepared that focused more on nanotechnology applications. As in the previous semester, students wanted greater emphasis placed on nanotechnology concepts during the hands-on activities with lower stress placed on LabVIEW programming skills.

Figure 8 provides a summary of student responses in the course exit survey for all three semesters. On average, about 18% of students expressed an interest in pursuing a nanotechnology minor or option. About 55% saw nanotechnology education relevant to their intended engineering major.

The results of the pre-and post-tests administered in the 2009 spring semester presented in Fig. 9 showed significant improvement in the student misconceptions that were also observed during the previous semesters. Compared to 48% students in the pre-test, about 85% appeared to have developed an awareness of various nanotechnology applications.

Since 149 students took the pre-test and 66 participated in the post-test, there were at least 35 students who participated in both tests. Thus at least 53% of the students participated in both tests. This leads us to assume that the results reflect a significant improvement in the students’ understanding of nanotechnology concepts. Student responses were analyzed to observe the influence of

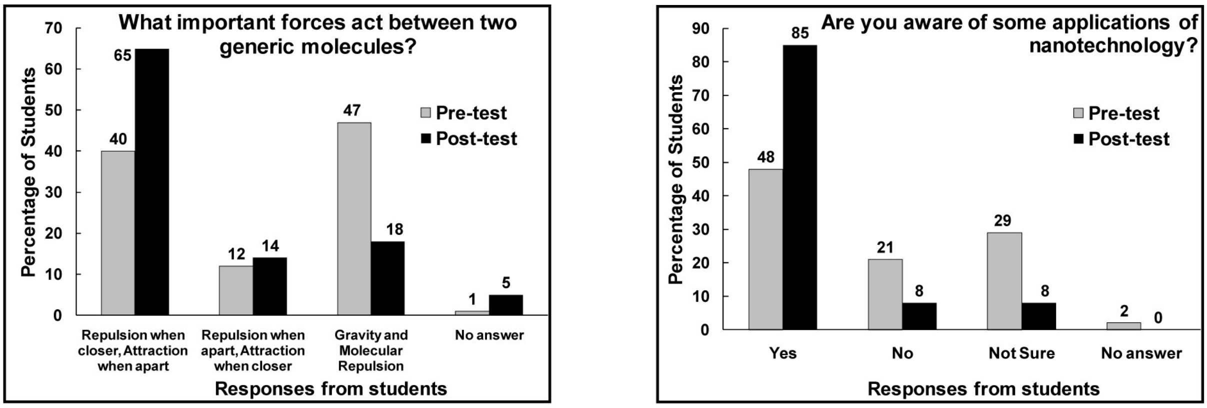


Fig. 9. Student responses to key questions asked of them during the pre-test (N=149) and again during the post-test (N=66) of the Spring '09 module implementation.

self-reported gender on their nanotechnology learning experiences. As shown in Fig. 10, 55% of male students and 20% of females expressed awareness of nanotechnology concepts in the pre-test. We do not have data to support either way whether this difference in prior knowledge between males and females is a function of their high school experiences. However, the post-test results showed that 85% students in both groups communicated knowledge of these concepts. This represents statistically significant increase in proportion of students, both males and females, demonstrating awareness of nanotechnology concepts at a significance level (alpha) of 0.001. We acknowledge the small data samples as a limitation of this study. It may be noted that students' participation in the pre-and post-tests was on a voluntary basis. This did affect students' participation rate particularly on the post-test since this was implemented toward the end of the semester when students get busy in wrapping up various course projects, assignments, reports, etc. Also, Tablet PC / DyKnow based formative assessment technique seems to have a great potential in developing a

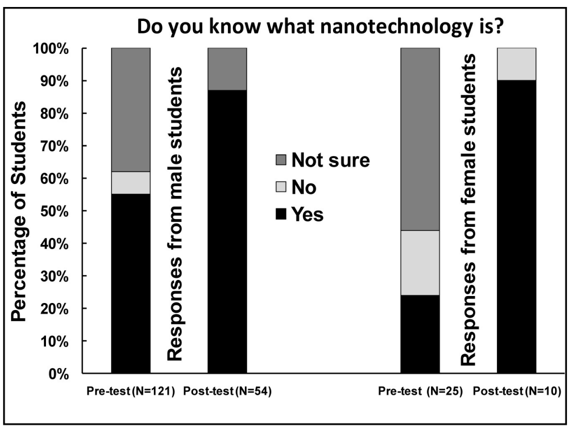


Fig. 10. Students' interest in nanotechnology assessed according to their gender.

feedback-loop in classroom and analysis of students' responses indicate positive learning experiences as a result of these technologies [53].

5. Conclusions

We have described a collaborative project between two engineering departments and an interdisciplinary university research institute at Virginia Tech to creating a nanotechnology option based on the well-established spiral theory. The option includes nanotechnology topics with increasing levels of complexity. We have provided details regarding the development of a freshman module that has been taught to approximately 1800 students. We found that a video presentation covering nanotechnology fundamentals for freshmen that exceeds twenty minutes in length is not well received by students and that students are eager to observe an actual nanotechnology experiment. The LabVIEW software offers a suitable environment to develop hands-on analysis activities for nanotechnology concepts. However, these activities should emphasize nanotechnology concepts more than the LabVIEW concepts. While we realize the benefit of hands-on activities in a laboratory setting to enhance the learning, the size of our program prevents us from doing so. About 18% of freshmen expressed interest in pursuing a nanotechnology option.

6. Ongoing and future work

We are currently discussing a number of issues:

(1) Are the current educational tools available to a typical engineering educator good enough to teach concepts associated with emerging technologies which are highly interdisciplinary in nature?
(2) Is the hands-on learning paradigm a good and

feasible one for all kinds of learning? How do we teach our students the power of abstraction especially when it comes to emerging technologies?

(3) How can we take advantage of the information technology skills of today's students (e.g., through their social networking, web browsing, online communication, and other habits) to facilitate the learning of emerging technology concepts?

We continue to explore these and other questions and welcome input and participation from our readers. Interested readers are also encouraged to contact the authors to obtain additional information about our nanotechnology curriculum. Further, this education theory-based curriculum development work motivated authors to successfully pursue another grant under the ethics education in science and engineering (EESE) program of the NSF. A spiral approach is considered to weave ethics instruction throughout the undergraduate curriculum in this EESE grant and authors have conducted workshops for faculty and graduate students for wider dissemination of this approach. A comprehensive survey is implemented in the entire College of Engineering for assessing the status of ethics instruction both in undergraduate and graduate curricula [52].

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Appendix A

List of questions with the multiple choices (italicized) for responses asked of students in the *pre-test* and *post-test* during the 2009 spring semester:

(1) Your intended area of engineering is:
(2) Gender (optional):
(3) Do you know what nanotechnology is?
Yes/No/Not Sure
(4) Nanotechnology involves (a) Research and technology development involving structures with at least one dimension in approximately the 1–100 nanometer range (b) Creating and using structures, devices and systems that have novel properties and functions because of their nanometer scale dimensions (c) Ability to control or manipulate on the atomic scale
All the above/Only a and b/Only b and c/ Only a and c/ None of these
(5) What is a nanometer?
10^{-12}m/10^{-10}m/10^{-9}m/10^{-6}m/10^{-4}m/Other
(6) Typically, what is the value of an atom's diameter?
10^{-12}m/10^{-11}m/10^{-10}m/10^{-9}m/10^{-8}m/10^{-6}m/Other
(7) What influences an apple as it falls from a tree?
The fluid drag on it from the surrounding air/Gravity/Gravity and fluid drag from the surrounding air/The earth's electric field/The earth's electric field and gravity and fluid drag/Sunspots/Sunspots and the earth's electric field and gravity and fluid drag
(8) What important forces act on two different generic molecules as they approach each other?
Attraction between molecules when they are far apart and repulsion between them as they come closer/ Repulsion between molecules when they are far apart and attraction as they come closer/The gravitational force and the molecular repulsion between molecules
(9) For how long do you think have scientists been formally working on nanotechnology?
Last decade/last twenty years/last fifty years/last century/last millennium
(10) Are you aware of some applications of nanotechnology?
Yes/No/Not Sure
(11) Nanotechnology can be used for the following applications: (a) Tissue Engineering (b) Water treatment/ filtration (c) Increasing energy (d) Semiconductor devices (e) Drug targeting
All the above/Only a,b,c/Only a,c,d/Only b,c,e/Only a,d,e/Only a,b,d,e/None of these
(12) What are the typical test samples/materials used in nanoscale experiments? Check all that apply
Human hair/Carbon Nanotube/Silicon Nanotube/Gold Nanoparticles/Bacteria

Ganesh Balasubramanian is a Ph.D. student in the Department of Engineering Science and Mechanics at Virginia Tech. He received his undergraduate degree in Mechanical Engineering from Jadavpur University, India in 2007. His doctoral research involves investigations of fluid flow and heat transfer across nanoscale interfaces using molecular simulations.

Vinod K. Lohani is a professor in the Engineering Education Department and an adjunct faculty in the Civil and Environmental Engineering at Virginia Tech. He received a Ph.D. in civil engineering from Virginia Tech in 1995. His research interests are in the areas of knowledge modeling, water and energy sustainability, engineering learning modules for freshmen, and international collaboration. He led a major curriculum reform project (2004–2009), funded under the department-level reform program of the NSF, at Virginia Tech. A spiral curriculum approach is adopted to reformulate engineering curriculum in bioprocess engineering in this project. He co-authored an award winning paper with his Ph.D. student (Dr. Jennifer Mullin) at the 2007 annual conference of ASEE. He received the College of Engineering Faculty Fellow award in 2008 and W. S. 'Pete' White Innovation in Engineering Education Award in 2010. His Ph.D. co-advisee (Dr. Ricky Castles) won third prize in a poster competition under the "Personalized Learning System" category at a Grand Challenges conference organized by the National Academy of Engineering at Duke University during March 02–03, 2009.

Ishwar K. Puri is Professor and Department Head of Engineering Science and Mechanics (ESM) at Virginia Tech. He obtained his Ph.D. (1987), and MS (1984) degrees in Engineering Science (Applied Mechanics) from the University of California, San Diego after obtaining a B.Sc. (1982) in Mechanical Engineering from the University of Delhi. He joined the University of Illinois at Chicago (UIC) in 1990 as an Assistant Professor in its Mechanical Engineering Department before moving to Virginia Tech in 2004. He is a Fellow of the American Society of Mechanical Engineers (ASME) and of the American Association for the Advancement of Science (AAAS).

Scott W. Case completed his Ph.D. studies at Virginia Tech in 1996 and began working as a post-doctoral research associate. He became a Research Assistant Professor in 1997, an Assistant Professor in 1998, and an Associate Professor in 2003. He was named Associate Department Head in Engineering Science and Mechanics in 2005. He and his co-authors have been recognized for best paper awards by the American Society for Composites and the American Composites Manufacturers Association. His teaching and research accomplishments resulted in him receiving the College of Engineering's Outstanding New Professor Award for 2002, being named a College of Engineering Faculty Fellow in 2004, and receiving the College of Engineering Dean's Award for Research in 2007.

Roop L. Mahajan is Director of the Institute for Critical Technology and Applied Science (ICTAS) at Virginia Tech where he also holds a joint appointment as tenured professor in the departments of Mechanical Engineering and Engineering Science Mechanics. His research interests include Bio-MEMS as sensors and actuators, Micro-fluidics, Thermal sciences, Artificial © American Society for Engineering Education, 2009 neural networks, Nanotechnology, Humanistic and Sustainable Engineering. He has published over 180 archival publications in these fields and has received national and international recognition worldwide for his research. He is the recipient of many awards and honors including Bell Labs Fellow, ASME Heat Transfer Memorial Award, ASME Charles Richards Memorial Award and ASME Ralph Coats Gold Medal. He received the Ph.D. degree in mechanical engineering from Cornell University, Ithaca, NY in 1977 and B.S. and MS degrees in mechanical engineering from Punjab University, India.