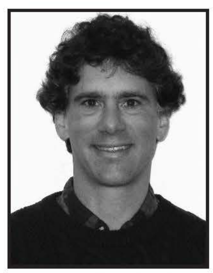
A NANOTECHNOLOGY PROCESSES OPTION IN CHEMICAL ENGINEERING

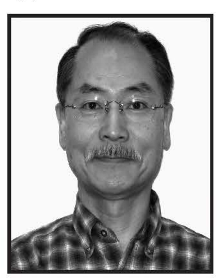
Milo D. Koretsky, Alexandre Yokochi, and Sho Kimura
Oregon State University • Corvallis, OR 97331-2702

With the substantial investment into the development of nanotechnology infrastructure for the 21st century and beyond, there is a need to adapt engineering and science curricula to equip students with the skills and attributes needed to contribute effectively in manufacturing-based processes that rely on nanotechnology.[1-3] The incorporation of nanotechnology into the undergraduate engineering curriculum represents both an opportunity and a challenge.[4] On the one hand, nanotechnology can revitalize undergraduate programs by engaging students with interesting nanotechnology-related concepts, examples, and experiments. On the other hand, due to its inherent interdisciplinary nature, programs will need to accommodate greater degrees of interdisciplinary teaching and research. Chemical and biological processes will play a significant role in the manufacturing operations. Chemical and biological engineers have the advantage of a solid background in chemical kinetics, reactor design, transport phenomena, thermodynamics, and process control to undertake the challenges in the high-volume manufacturing of nanotechnology-based products. Thus, these processes fall well within the purview of chemical and biological engineering undergraduate programs. At the same time, however, the products rely on principles based on other disciplines such as physics, mechanical engineering, and electrical engineering. Thus research and development of new processes based on new products is inherently interdisciplinary in nature. Chemical and biological engineers



***Milo Koretsky** is an associate professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received his B.S. and M.S. degrees from UC San Diego and his Ph.D. from UC Berkeley, all in chemical engineering. He currently has research activity in areas related to thin film materials processing and engineering education and is interested in integrating technology into effective educational practices and in promoting the use of higher-level cognitive skills in engineering problem solving.*

***Alex Yokochi** is an assistant professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received a B.S. and M.S. from Southern Illinois University at Carbondale and Ph.D. from Texas A&M University, all in chemistry. His research and teaching interests include the development of methodology to produce large volumes of engineered nanoparticles with well defined size and/or composition for various applications.*



***Sho Kimura** is a professor in the School of Chemical, Biological, and Environmental Engineering at at Oregon State University. He received his B.S. and Ph.D. degrees from Osaka University, Japan, and M.S. degree from Oregon State University, all in chemical engineering. He teaches Material Balances and Stoichiometry, Material and Energy Balances in Nanotechnology, and Chemical Plant Design I & II. His research interests include synthesis of carbon and silicon carbide nanotubes.*

will also play a vital role in this development as nanosystems evolve to include active nanostructures, 3-D nanosystems and systems of nanosystems, and heterogeneous molecular nanosystems.[2] The curricular challenge that needs to be addressed is how to design a program that reinforces the ChE undergraduate's core skills (depth) in a way that can be applied toward manufacturing nanotechnology-based products while simultaneously providing the breadth to interact effectively on the multidisciplinary teams that span the wide range of opportunities enabled by this emerging area.

It has been proposed that as the chemical engineering profession takes its next evolutionary step toward applying molecular scale engineering to a set of new and emerging technologies, the core undergraduate curriculum needs associated reform.[5] As topics from these emerging molecular-based technologies are incorporated, however, there is a legitimate concern of dilution of the core content due to staffing issues.[6] At Oregon State University (OSU), the Chemical, Biological, and Environmental Engineering programs have recently joined into a single administrative structure. This structure alleviates the staffing issue in two ways. First, a significant portion of the courses for all three programs is jointly taught. This set of 11 core courses covers fundamentals germane to all three disciplines (*e.g.*, material and energy balances, transport processes, thermodynamics, and process data analysis) while reducing the number of instructors needed. Second, the Option areas in chemical engineering are taken from topics that have core research faculty. In two of the Options, biological processes and environmental processes, chemical engineering students take elective classes from among those offered by the other programs. In this way, some of the key elements identified in the "New Frontiers in Chemical Engineering Education" workshops are integrated into the undergraduate curriculum while, simultaneously, holding students accountable for the same depth of learning that has served OSU ChE graduates for many years. Moreover, this integration is accomplished in a reasonable scope commensurate with the resources of the program.

This paper presents the curriculum developed to incorporate nanotechnology education in the chemical engineering program at Oregon State University. The approach is twofold: 1) to develop a Nanotechnology Processes Option in the Chemical Engineering Program and 2) to develop two new sophomore-level courses: a survey course that is broadly available to all engineering undergraduates and a discipline-specific laboratory course that allows students to synthesize the engineering science content toward the application of nanotechnology. The curricular development fits in well with the growing research and commercialization activity of the Oregon Nanoscience and Microtechnologies Institute (ONAMI), and is consistent with the evolutionary vision developed by leading chemical engineering educators in the three-workshop series "New Frontiers in Chemical Engineering Education."[5]

NANOTECHNOLOGY PROCESSES OPTION IN CHEMICAL ENGINEERING

To meet all the ABET engineering topics and advanced science requirements, ChE students are required to take five to six technical elective classes outside the ChE core. These courses may be taken in any area as long as they have the appropriate engineering or science content as prescribed by ABET and AIChE. When taking the courses in an *ad hoc* manner, however, students have indicated that they get little satisfaction or career enhancement. The ChE Department has established Options to aid students in selection of elective courses. Options also help to broaden and strengthen the undergraduate ChE curriculum, potentially attracting more students to the department. To be eligible for an Option, the student must fill out and present a Student Petition for Option Program in Chemical Engineering to the faculty "champion" for the desired area. The champion is a faculty member with expertise in the area of the Option. Additionally an Option must contain at least 21 credits. Three Options

TABLE 1
Nanotechnology Processes Option

Class #	Credits	Title
ENGR 221	3	The Science, Engineering and Social Impact of Nanotechnology (a)
ChE 214	4	Material and Energy Balances in Nanotechnology (a/b)
ChE 416	3	Chemical Engineering Lab III (b*)
ChE 417	4	Analytical Instrumentation in Chemical, Environmental and Biological Engineering (a/b)
ChE 444	4	Thin Film Materials Processing (a/b)
	3	Elective

a Lecture course
b Laboratory course
* The capstone laboratory project will be in the area of nanotechnology

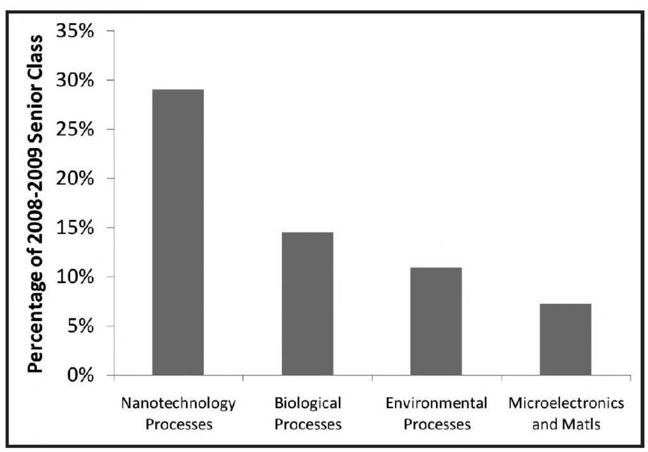


Figure 1. *Percentage of 2008-2009 graduating seniors enrolled in each of the four ChE Options at OSU.*

have been available at OSU: 1) Biochemical Processes; 2) Environmental Processes; and 3) Microelectronics Processes and Materials Science. These areas correspond to strengths in the OSU ChE program. A fourth Option, the Nanotechnology Processes Option, has recently been developed. An outline of the curricular requirements is listed in Table 1. It contains six courses—five required courses and an elective—and includes two sophomore-level courses. Four of the five required classes are laboratory-based and emphasize hands-on experiential learning.

The Science, Engineering, and Social Impact of Nanotechnology (ENGR 221) is a general engineering survey course that provides students from Chemical, Biological, Electrical, Environmental, Industrial, Manufacturing, and Mechanical Engineering exposure to the field of nanotechnology; therefore, there is inherently a multidisciplinary approach. On the other hand, Material and Energy Balances in Nanotechnology (ChE 214) is a ChE-specific laboratory-based course, emphasizing how the fundamental skills students have learned in material and energy balances couple to nanotechnology. For ChE students, the approach is to provide students both a breadth of multidisciplinary experiences and a depth of specific technical applications within the discipline. Thus, they are exposed to these complementary experiences early in their undergraduate studies. These sophomore-level courses lead into three upper-division courses already in place. This duality (Breadth plus Depth Pedagogy) is reinforced in senior laboratory (ChE 416), through which students synthesize both aspects in their capstone project, and potentially through their Honors College thesis.

The Nanotechnology Processes Option was approved at the university level in Fall 2006. Since two of the required courses are at the sophomore level, the first graduates became available three years later, at the end of the 2008-09 academic year. Figure 1 shows the distribution of senior students enrolled in the four Options available in the ChE Program for 2008-09. Of the 55 seniors in Chemical Engineering, 34 have chosen to pursue an Option. The Nanotechnology Processes Option has the most students subscribed, representing 16 students or 29% of the total ChE seniors.

ENGR 221—THE SCIENCE, ENGINEERING, AND SOCIAL IMPACT OF NANOTECHNOLOGY

The Science, Engineering, and Social Impact of Nanotechnology, ENGR 221, is a general engineering survey course with the objective of ensuring all engineering students have access to a course offering basic understanding of the engineering field of nanotechnology. The course learning objectives are presented in Figure 2. The concepts of nanotechnology have been divided into one- to two-week sections, and include applications, properties on the nanoscale, processing, characterization, ethics, and health and safety. The course includes several features intended to promote active learning, including hands-on activities and demonstrations and a final ethics project where students complete a risk assessment of the impact of nanotechnology on society. In addition to introducing technical knowledge surrounding the field of nanotechnology, a goal of this course is to prompt students to synthesize some of the fundamental concepts in science and engineering that they have been taught within the context of nanotechnology.

In the two-hour recitation each week, hands-on activities are completed. Two such hands-on activities are described below. For the section on nanoscale characterization, a scanning electron microscopy (SEM) activity was developed. During this activity, students use a FEI Phenom SEM simulator software program in a virtual laboratory to view a variety of SEM samples, from mosquitoes to a crystal of salt. A screenshot of this simulation and a picture of students performing this

After successful completion of this course, students become able to:

1. Define nanotechnology.
2. Discuss how nanotechnology may impact society.
3. Identify products based on nanostructured materials.
4. Explain how the properties of nanostructured materials differ from their non-nanostructured (conventional) material counterparts.
5. Explain how these unique properties may adversely impact human health and the environment; define the concerns with nanotoxicity research and summarize the status in this area.
6. Explain the difference in approach of top-down and bottom-up manufacturing methods.
7. Describe major manufacturing methods used to produce nanostructured materials and devices and discuss issues in this area.
8. Identify some common methods used for nanomaterials characterization; describe the principles by which each method works and the type of information obtained.
9. Compare two prevalent ethical theories, utilitarianism and absolutism.
10. Perform a risk assessment to determine the best direction for nanotechnology development.

Figure 2. *Course Learning Objectives for ENGR 221.*

activity are shown on the right side in Figure 3. The simulation allows students to become familiar with the measurement technique and the software. It is followed by a hands-on activity, shown on the left in Figure 3, where students in the class prepare actual SEM samples of their hair, examine these samples using a FEI Phenom benchtop SEM, and analyze the results. This analysis is related back to a "scale of things" activity they completed earlier in the term.

A second laboratory, making ferrofluids,[7] was delivered to integrate two learning outcomes: properties of nanostructured materials and nanomaterials processing. The context of this laboratory follows. Midway through the class, the topic of magnetic fluids is introduced. Two lecture hours are spent discussing the properties of magnetic materials and, specifically, ferrofluids. Topics covered in lecture include: electron configurations of iron and their magnetic effect, crystal structure of several iron oxides, forces on a particle in suspension, reasons only particles on the nanoscale can be used to create ferrofluids, and the relation of the lifetime of the magnetic moment to temperature and volume of the particle. The week after this lecture material is presented, students engage in a hands-on laboratory in which a ferromagnetic fluid is used to allow students to observe the unique properties that are found at the nanoscale. The objective of the laboratory is to reinforce learning on the subjects discussed in lecture the week before. This activity involves the preparation of nanocrystalline-mixed valence iron oxide followed by the addition of an ionic surfactant to create a ferrofluid. Concepts reinforced by this exercise include the importance of understanding the structure of matter (the difference between Fe_2O_3 and Fe_3O_4) and the importance of correct stoichiometry in materials synthesis.

From physics[8] to chemical engineering,[9] active learning practices in the classroom, such as the use of ConceptTests, have been proven to effectively increase student learning. By having students vote by "a show of hands," this method has been reported to be effective in student learning of nanotechnology.[10] In an effort to promote such active learning in students and to provide opportunities for formative assessment, we have employed a technology-enabled learning tool. The Web-based Interactive Science and Engineering (WISE) learning tool was developed at OSU to use the College of Engineering's Wireless Laptop Initiative, which requires all undergraduate engineering students to own a wireless laptop. The WISE learning tool allows an instructor to pose to the class questions that probe for conceptual understanding and supports a variety of student response types.[11] After the students have submitted their response, the instructor can review a summary of the results with the class. This tool allows for peer instruction,[12] classroom instruction,[13] or a combination of such active learning practices. For example, a screenshot from WISE of a ConceptTest is shown in Figure 4. This screenshot shows the results that were displayed to the class after individual responses were submitted. The question explores the relationship between a materials property (temperature) of a solid and its surface-area-to-volume ratio. The concept of the size-dependent properties based on surface-to-volume ratios is central to the understanding of nanotechnology, but difficult for many students.[14] Students were asked to select among four possible multiple choices and explain their choice in a short-answer follow-up. The instructor then selected sample responses and displayed them to the class. The results to the multiple-choice questions are shown by the bar graph in Figure 4 and the short answers for three selected cases are displayed below. One of these responses shows a sound understanding of surface-to-volume ratio and its relationship to temperature change. Based on this response, the students divided into peer groups and discussed their answers. When the question was asked again, 21 students answered correctly, although not always with an explanation that clearly demonstrated understanding. The improvement of this type of active learning exercise (32% to 75%) is consistent with that reported in the physics literature.[8]

Figure 3. *Laboratory-Simulation hybrid of scanning electron microscopy (SEM) activity.*

ENGR 221 was delivered for the first time in Winter 2007 with an enrollment of 31, and again in Winter 2008 with an enrollment of 45. The course was assessed in terms of the achievement of the learning objectives and the effectiveness of the different modes of delivery used during the course. Assessment methods for this course primarily relied on pre- and post-assessments of one kind or another. Overall course pre- and post-concept inventory assessments were administered, in addition to pre- and post-worksheets for two class activities. The other major methods of assessment of student learning were an end-of-term survey and an analysis of critical thinking of the final ethics paper. One of the interesting results is from analysis of an end-of-term survey that asked students to discuss in more detail one concept from their previous coursework that they applied, and how it related to nanotechnology. These responses were then coded according to Shavelson's cognitive model, which defines achievement in science as consisting of four types of knowledge: declarative knowledge ("knowing that"), procedural knowledge ("knowing how"), schematic knowledge ("knowing why"), and strategic knowledge ("knowing when, where, and how our knowledge applies").[15] Declarative knowledge includes facts and definitions. Procedural knowledge refers to knowledge of the sequences of steps that can be executed to complete a task, whether in the laboratory or to solve a problem. Schematic knowledge includes principles, schemas, and mental models that explain the physical world. Of the 32 responses, 21 were classified as containing elements of schematic knowledge. Students showed a conceptual understanding of the material they discussed; they were able to take concepts introduced in other classes, build on them in the context of nanotechnology, and develop that knowledge into a strong, conceptual understanding of both the basic material and its relation to nanotechnology. Schematic learning is valuable due to its transferability. The high percentage of students displaying this type of learning indicates achievement towards one of the course goals—having students synthesize fundamental concepts in science and engineering within the context of nanotechnology. The detailed assessment is presented elsewhere.[16]

It is believed that the pedagogical features discussed above play a significant role in the success at promoting the student's use of schematic knowledge, even at the sophomore level. This approach is consistent with the successes of scientific teaching in biology.[17] These methods encourage students to construct new knowledge and develop scientific ways of thinking, and they provide students and instructors feedback about learning. While the discussion above illustrates these pedagogical features in the context of nanotechnology, this approach can be applied to any course in the chemical engineering curriculum.

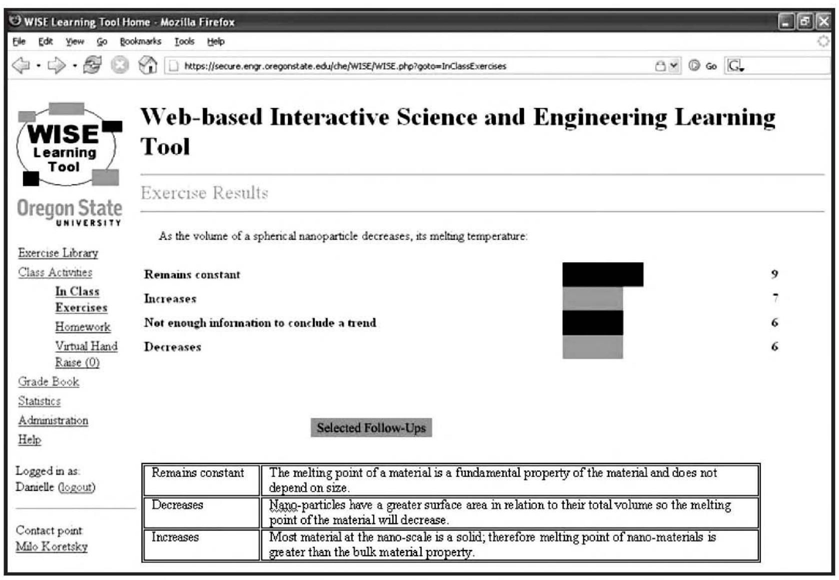


Figure 4. *Screenshot from the Web-based science and engineering (WISE) learning tool.*

CHE 214—MATERIAL AND ENERGY BALANCES IN NANOTECHNOLOGY

Material and Energy Balances in Nanotechnology, ChE 214, is a chemical engineering laboratory course intended to give students an immediate way to apply what they learned in Material and Energy Balances (the first strongly technical chemical engineering courses students take) in the context of a hands-on nanotechnology laboratory. The course learning objectives are presented in Figure 5. Comparison of these learning objectives with those of ENGR 221 (Figure 2) reveals their complementary intent of depth and breadth. For most

After successful completion of this course, students become able to:

1. Quantitatively describe the rate of reaction through real-time measurements of changes in the mass of product carbon nanotubes.
2. Calculate molar and mass concentrations based on flow rates of mixture-gas components and correlate them to GC based concentrations.
3. Calculate the fractional conversion of limiting reactant based on the reactant inlet and outlet flow rates.
4. Calculate product yields based on the gas-flow rates and correlate them to mass-based product yields.
5. Use temperature measurements at the reactor inlet and outlet to explain heats of reaction in conjunction with endothermic and exothermic reaction concept.
6. Predict reactor outlet temperature and compare it to actual temperature measurements.

Figure 5. *Course Learning Objectives for ChE 214.*

students, this course will directly follow ENGR 221, and they will already have completed a survey course in nanotechnology. ChE 214 is a laboratory course, consisting of a two-hour lecture period and a four-hour laboratory period each week. Each laboratory is not an isolated occurrence, but instead builds on the previous laboratories. For example, the catalyst the students prepare in the first laboratory is used throughout the course to grow nanotubes. The lecture periods consist of one hour of new material followed by an hour-long quiz. Students are given weekly homework assignments intended to prepare them for laboratory.

In this course students grow carbon nanotubes from ethylene in three different reactors: a thermo gravimetric analyzer (TGA), a vertical packed-bed reactor, and a plasma reactor. The TGA is used to make real-time measurements of the growth rate of carbon nanotubes by measuring the change in mass with time. Based on a group's choice, either the temperature dependence or the concentration dependence of the growth rate have been studied. The vertical packed-bed reactor, shown in Figure 6, is used for batch-wise synthesis of carbon nanotubes in large quantities using the reaction conditions of the group's choice, as determined by the TGA experiment. Figure 6 also shows a photograph of the nanotubes one of the groups grew, and an SEM that they took of their product. In the two years that this course has been offered, six student groups have each produced between 3 and 8 g of nanotubes in a single run using this reactor. Finally, in one of the laboratory sessions, students use a plasma reactor to grow carbon nanotubes. This experience allows them to contrast a system for high-volume manufacture of bulk nanotubes and a system for high-value manufacture for nanoelectronics applications.

The students are required to predict the amounts of product nanotubes based on the rate data obtained with the TGA as well as the changes in the gas compositions and flow rates between the reactor inlet and outlet streams. They should then discuss any differences between the predictions and the actual product mass. They are also required to predict increases in temperature based on an adiabatic reaction assumption, compare their predictions with the measured increases in temperature between the inlet and outlet gas streams, and discuss possible causes for the deviations between the theoretical predictions and actual measurements. In these ways, they are prompted to reconcile their experimental results with their conceptual understanding of material and energy balances that they have learned earlier in the year. The intent is to promote an integrated construction of knowledge in students of both chemical engineering fundamentals and nanotechnology.

As a course specific to chemical engineering, ChE 214 has been exclusively taken by chemical engineering majors. There were 14 students who completed the course in Spring 2007 and 12 in Spring 2008. The demographics changed considerably in the two years the course was offered. In 2007, there were 13 sophomore students and one senior while in 2008 there were six sophomore students and six seniors. Again, the course was assessed in terms of the achievement of the learning objectives.[16] Since the course consisted primarily of laboratory sessions, observations and survey of these sessions were the primary tools of assessment. In addition, pre- and post-tests were administered, along with an end-of-term survey and analysis of the final project reports (which covered most material introduced in the course). The survey was intended to reveal the students' perception of what they were expected to learn and the concepts they employed in each laboratory. Again, the responses to each question of each survey were categorized in terms of declarative, procedural, or schematic knowledge. The first conclusion from this analysis is that seniors are better able to think about the laboratory material schematically than sophomores. A second conclusion is that students are more able to respond schematically when asked directly about a concept than they are when asked about what they were intended to learn in the laboratory. In fact, when asked about what they learned in laboratory, students are much more likely to demonstrate procedural knowledge and describe the physical system and its operation rather than the concepts behind why the system behaves as it does. This result is especially true for sophomore students.

NANOTECHNOLOGY-BASED CAPSTONE LABORATORY PROJECTS

Students who select the Nanotechnology Processes Option are required to do a nanotechnology-based capstone project as the major project in Chemical Engineering Lab II and

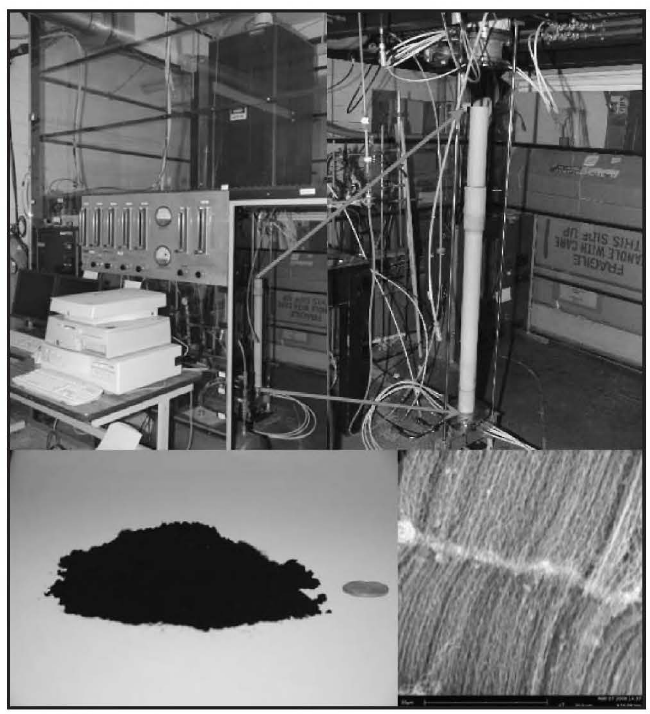


Figure 6. *Thermal chemical vapor deposition of carbon nanotubes in ChE 214.*

III (ChE 415 and 416). The deliverables for the 15-week capstone project include participation in a poster session at OSU's "Engineering Week," where graduating seniors from all departments in the College of Engineering display their senior project work, an oral presentation at an internal mini-symposium organized specifically for the purpose, and a final technical written report. In addition to the projects, the instructors offer a short subset of the lectures focused on a very brief survey of nanotechnology at a level appropriate for seniors, to ensure that those students that have not elected to work on a nanotechnology-related project have a general understanding of nanotechnology.

While the first batch of students in Nanotechnology Processes Option did not reach the senior level until 2008-2009, two laboratory projects were conducted by students in 2005-2006 and three projects were conducted by students in 2006-2007. Five student groups have completed nanotechnology-based senior projects in 2008-2009. These projects have been constructed to be of a broad enough scope so that those students who were capable would be encouraged to apply schematic and strategic knowledge of chemical engineering science while others who engaged more consistently using procedural knowledge could still complete a meaningful project. The 10 projects that have been conducted to date are listed in Table 2.

STUDENT SURVEY

After completing the sophomore-level nanotechnology course or courses, students were given a survey with two parts. In the first part, they were asked to rate the extent to which the courses assisted them to make connections to content from other courses, pursue a career in nanotechnology, and increase their interest in nanotechnology. Students rated these aspects on a Likert scale of 1-5, with 1 as a strongly disagree and 5 as a strongly agree. The average results are shown in Table 3. The second part of the survey asked students to rate the effectiveness of the courses in improving their ability to perform several categories of tasks, on a Likert scale of 1-5 (as in the previous question). The average results for each task are shown in Table 4.

The students believed that the sophomore-level content was useful toward pursuing a career (4.37), but did not believe the courses increased their interest (3.03); perhaps because those students who selected these courses already had an interest. They moderately agreed that the content helped them make connections to other courses (3.63); however, many more students took only ENGR 221 than took both courses. The perception of an increase in skills and abilities by the sophomore-level course(s) was rated high, with students feeling strongly that they could work successfully on a team (4.68), demonstrate understanding and application of principles in nanotechnology (4.58), and identify the nature of a design problem (4.53).

TABLE 2
Nanotechnology-Based Senior Projects in Chemical Engineering

Project Title	Description	Year
Production of Aligned Carbon Nanotubes	The assembly of a reactor for the production of aligned films of carbon nanotubes using ethylene pyrolysis on iron catalysts and growth of carbon nanotubes by ethylene pyrolysis.	2005-2006
Nanocrystalline Photovoltaic Devices	Preparation of photovoltaic devices by spin coating nanocrystalline precursors onto polymeric substrates.	2005-2006
Production of Aligned Carbon Nanotubes	The assembly, testing, and operation of a system designed to produce films of aligned carbon-nanotubes on a surface using pyrolysis of ethanol on molybdenum acetate (Mo_2OAc_4) based catalysts.	2006-2007
Nanostructured Polymers	The use of diatom skeletons as masks to plasma-etch nanostructured designs onto polymeric surfaces.	2006-2007
Magnetic Nanocomposites	The production of Fe/Fe_2O_3 magnetic nanocomposites by sol-gel processing of $Fe/Fe(acac)_3$ precursors.	2006-2007
Exploration of Low-Cost Implementation of Reactive Systems in Microreactors	Development of low-cost, inkjet-based contact lithography and wet etching of glass to produce a microchannel-based reactor and demonstration with alkaline hydrolysis of ethyl acetate solutions in water.	2008-2009
Microreactor-Enhanced Redox Flow Cell Battery	Construction of a redox flow cell zinc-bromine secondary battery suitable for energy storage research and demonstrations.	2008-2009
Sputtering Metal Films for Microelectronics: Forming Barrier Layers Using CuX Targets	Demonstration and characterization of self-formation barrier technology using sputtered CuMn blanket films followed by thermal anneal.	2008-2009
Nanobiosensors	Protein-sensitive field effect transistors manufactured commercially available silicon-on-insulator wafers. The final devices are high performance (specific detection below 100 fM) and are commercially exciting.	2008-2009
Synthesis of Doped Titanium Dioxide Nanoparticles	Synthesis of TiO_2 nanoparticles that are doped with an indicator element that is detectable by ICP-AES. The objective of this work is to demonstrate proof-of-concept for further work involving use of more expensive lanthanides as dopants. Ultimately, the doped nanoparticles will be used in experiments examining the fate and transport of nanomaterials in the environment.	2008-2009

CONCLUSION

The implementation and assessment of the Nanotechnology Processes Option in Chemical Engineering at Oregon State University has been described. Its foundation builds upon two newly developed sophomore-level courses: a general engineering survey course that exposes students to the scientific basis, potential technological and societal implications of nanotechnology, and a ChE-specific laboratory-based course that integrates the fundamental knowledge students have learned in Material and Energy Balances with Nanotechnology. The approach is to provide students with both a breadth of multidisciplinary experiences and a depth of specific technical applications within the discipline early in their undergraduate studies. In addition, nanotechnology-based capstone projects have been integrated into the senior laboratory class, with 10 different student teams participating to date. Nanotechnology-related content has also been added to two senior-level courses that are part of the Option.

The Option described contains a coherent set of courses that have been constructed to elicit high cognitive levels in students beginning early in the curriculum. Initial assessment of this approach is positive. Effort will be required, however, to keep the content up-to-date as the technology rapidly evolves. Additionally, the sophomore-based laboratory course has a large overhead per student served, requiring both institutional support and instructor dedication to continue.

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REFERENCES

1. Fonash, S.J.,"Education and Training of the Nanotechnology Workforce," *J. Nanoparticle Res.*, **3**, 79 (2001)
2. Roco, M.C., "Nanoscale Science and Engineering: Unifying and Transforming Tools," *AIChE Journal*, **50**, 890 (2004)
3. Roco, M.C., "Nanotechnology—A Frontier for Engineerign Education," *Int. J. Eng. Ed.*, **18**, 488 (2002)
4. Schank, P., J. Krajcik, and M. Yunker, "Can Nanotechnology Education be a Catalyst for Educational Reform," in *Nanoethics: The Ethical and Social Implications of Nanotechnology*, Wiley- Interscience, Hoboken, NJ (2007)
5. "Frontiers in Chemical Engineering Education," CCR/NSF Workshops, <http://mit.edu/che- curriculum/index.html> Accessed 7/15/08
6. Shaeiwitz, J., and R. Turton, "The Changing ChE Curriculum—How Much Change is Appropriate," *Proceedings of the 2006 American Society for Engineering Education Annual Conference & Exposition* (2006)
7. Crone, W.C., A.B. Ellis, A.C. Payne, K.W. Lux, A.K. Bentley, R.W. Carpick, D. Stone, G.C. Lisensky, and S.M. Condren, "Incorporating Concepts of Nanotechnology into the Materials Science and Engineering Classroom and Laboratory," *Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition* (2003)
8. Hake, R.R., "Interactive-Engagement vs. Traditional Methods: A 6,000-Student Survey of Mechanics Test Data for Introductory Physics Courses," *Am. J. Phys.*, **66**, 64(1998)
9. Falconer, J.L., "Use of ConceptTests and Instant Feedback in Thermodynamics," *Chem. Eng. Ed.*, **38**, 64 (2004)
10. Condren, S.M., J.G. Breitzer, A.C. Payne, A.B. Ellis, C.G. Widstrand, T.F. Kuech and G.C. Lisensky, "Student-Centered Nanotechnology-Enriched Introductory College Chemistry Courses for Engineering Students," *Int. J. Eng. Ed.*, **18**, 550 (2002)
11. Koretsky, M.D., and B.Brooks, "A Web-Based Interactive Science and Engineering Learning Tool that Promotes Concept-Based Instruction," *Proceedings of the 2008 American Society for Engineering Education Annual Conference & Exposition* (2008)
12. Mazur, E., *Peer Instruction: A User's Manual*, Prentice–Hall, Upper Saddle River, NJ (1997)
13. Dufresne, R.J., W.J. Gerace, W.J. Leonard, J.P. Mestre, and L. Wenk, "Classtalk: a Classroom Communication System for Active Learning," *J. Computing in Higher Ed.*, **7**, 3 (1996)
14. Light, G., S. Swarat, E.-J. Park, and D. Drane, "Student Understanding of 'Surface Area to Volume Ratio' and its Relationship to Property Change in the Nano-science Engineering Context," Research in Engineering Education Symposium (2008)
15. Shavelson, R.J., M.A. Ruiz-Primo, and E.W. Wiley, "Windows of the Mind," *Higher Education*, **49**, 413 (2005)
16. Koretsky, M.D., A. Yokochi, S. Kimura, and S.Herzog, "Elements of Student Learning in Nanotechnology," *Int. J. Engng. Ed.*, in review.
17. Miller, S., C. Pfund, C. Maidl Pribbenow, and J. Handelsman, "The Pipeline: Scientific Teaching in Practice," *Science*, **322**, 1329 (2008) ❒

TABLE 3
Ratings Represent Student Agreement With Each of the Three Statements

Statement	Average Rating
The content helped me make connections to what I learned in other courses.	3.61
The content will help me in pursuing a career in nanotechnology.	4.37
The courses have increased my interest in nanotechnology.	3.03

TABLE 4
Student Perception of Ability Increased By the Sophomore Course(s)

Task	Average Rating
Identify the nature of a design problem or challenge related to nanotechnology	4.53
Demonstrate my understanding and application of principles in nanotechnology	4.58
Communicate the principles of nanotechnology in speech and writing to a wide audience of peers and experts	4.13
Work with a team to successfully complete large scale projects	4.68