Undergraduate and Graduate Education Plan for the Nanoscale Science and Engineering Center for High-Rate Nanomanufacturing

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Abstract

The academic partners in the Center for High-rate Nanomanufacturing (CHN), an NSF-sponsored Nanoscale Science and Engineering Center (NSEC), have created a comprehensive education program for the Center. All three core academic institutions, Northeastern University (NEU), the University of Massachusetts Lowell (UML), and the University of New Hampshire (UNH), have been leaders in advancing engineering education and in providing outreach activities to high school students, undergraduate and graduate students, science teachers, and industry. This paper focuses on the strategies for undergraduate and graduate student education.

With the three-campus Center and advances in on-line education, opportunities for collaborative development of unique cross-disciplinary and cross-university courses are possible. Three sets of nanomanufacturing courses will be offered to undergraduate students at all three campuses. Introductory course modules, designed to fit into existing freshmen science and engineering curricula, should prepare and motivate these students to become interested in the challenges associated with nanotechnology. Similar courses developed for non-science and non-engineering majors are intended to broaden the technological understanding of these students. Senior capstone design projects (in engineering) and senior thesis projects (in the sciences) are the basis for interdisciplinary, industry-sponsored projects in nanomanufacturing. Implementation of these course activities is expected to begin in the spring semester of 2005, and outcomes will be reported. The primary evaluation of this activities related to this education plan will be conducted by the Research and Evaluation Group of the University of Massachusetts, Amherst, Donahue Institute.

Introduction: The Proposal

The plan was simple. As shown in Table 1, the three universities would offer four collaboratively developed, interdisciplinary courses to students at all three campuses and disseminate these courses to other programs in the country. An undergraduate "Introduction to Nanomanufacturing" course was planned fit within existing freshman introductory engineering courses at all three institutions and within freshman seminar courses in some science programs. The freshman material was intended to prepare and motivate in-coming students to become interested in the challenges associated with nanotechnology. A nanomanufacturing capstone course would support cross-university, cross-disciplinary senior design or thesis projects. Capstone design projects (in engineering) and senior thesis projects (in the sciences) would be the basis for interdisciplinary, industry-sponsored projects in nanomanufacturing. Graduate students at all three universities could also enroll in a common graduate-level nanomanufacturing course, which would provide the foundations for students to pursue advanced research in nanomanufacturing.

Finally, a nanomanufacturing course would be offered for non-science and non-engineering students to satisfy part of their liberal arts core requirements.

Table 1. The Proposed Courses

Year	NEU	UML	UNH
1	Introduction to Nanomanufacturing		
2/3	Science/technology elective for non-science/non-engineering majors		
4/5	Nanomanufacturing Capstone Course		
G	Nanomanufacturing		

This plan seemed viable and had the support of the Engineering Deans at Northeastern University, the University of New Hampshire, and the University of Massachusetts Lowell. Initial discussions, however, showed that this plan would not be easy to implement. Specific issues included:

- The freshman courses were loaded with content, some of which was deemed critical to various disciplines, and therefore, could not be replaced.
- Other projects were also competing for "space" in the freshman courses. For example, a design and build module was incorporated into UML's "Introduction to Engineering I" as part of a college-wide service learning initiative, a project module is required for freshmen in NEU's introductory engineering course, and the freshmen seminar for UNH's chemistry students is intended to provide an overview of the profession.
- There was considerable interest in incorporating nanomanufacturing concepts into other parts of the curricula, particularly adding content to existing undergraduate courses and developing new discipline-specific technical electives and graduate courses.
- The cross-university capstone projects presented a number of logistical problems, including project-student matching, travel time, and the asynchronous academic calendars of the three universities. In addition, more than 50% of NEU capstone projects are done in collaboration with an external sponsor who provides some financial support as well as technical mentoring to supplement the faculty advisor. Science students at UNH have performed optional senior thesis projects, rather than required engineering capstone projects. Moreover, the cross-university capstone projects would need to mesh with UML's current implementation of cross-disciplinary service learning-based engineering capstone projects.
- More than one graduate course was needed to cover the content required for nanomanufacturing.

As a starting point, the CHN team decided to launch a graduate course and further examine existing course materials for nanoscience, nanotechnology, and nanomanufacturing.

What's Out There?

Eight Nanoscale Science and Engineering Centers were established prior to 2004. These Centers tend to leverage existing programs as well as new funding to produce education programs for graduate and undergraduate students. The bulk of the courses have been geared for graduate students and for use as senior electives. The Center for Biological and Environmental Nanotechnology (Rice) has developed a number of interdisciplinary graduate-level science courses, including "Science Policy and Ethics;"[1] new masters programs in Nanoscale Physics, Environmental Analysis and Decision Making, and Subsurface Geoscience[2,3]; undergraduate courses such "Nanotechnology: Content and Context;" undergraduate modules[4]; and modifications to existing senior and graduate-level courses[5,6]. While the Center for Integrated Nanopatterning and Detection Technologies's website[7] (Northwestern) lists no courses, a number of courses with nanotechnology content are offered in the mechanical and electrical engineering departments[8]. In spring 2003 and 2005, the Center for the Science of Nanoscale Systems and their

Device Applications (Harvard) offered a single interdisciplinary course, "Applied Physics 298: Interdisciplinary Chemistry, Physics, and Engineering,'' in spring 2003 and 2005, in which Center faculty lectured on "particular aspects of nanoscale research and discussed possible new applications."[9]. A similar approach was used by the Center for Directed Assembly of Nanostructures (RPI) for its "Nanostructured Materials" course[10]. This course was modified as an interactive undergraduate course, which can be delivered asynchronously to the partner institutions[11]. A separate course, "Introduction to Nanoscience" is offered at partner institution, the University of Illinois Urbana-Champaign[10,11]. At the Center for Electron Transport in Molecular Nanostructures (Columbia), there were 10 graduate courses for the 2004-2005 academic year (as compared to one per year for the previous two years). The Center is also offering short (two-day) courses designed to enhance the professional development of the Center's students[12]. A January 2003 offering, "The Ethical Conduct of Research" attracted 20 students[13], whereas attendance at "Nanoscience Safety" (May 2004) was simply required of all Center students and post doctoral researchers[14]. In contrast, the Center for Nanoscale Systems (Cornell) sited a single course, "Introduction to Nanoscience and Nanoengineering" designed to interest about 48 freshmen per semester[15]. Finally, the newer Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (UIUC) has elected a hybrid approach, in which two new graduate courses are being offered – one at UIUC and the other at a partner institution – and nano content has been added to another eight junior, senior, and graduate-level courses[16].

Recently, the National Science Foundation also awarded Northwestern University a grant to create the first Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT). A partnership between Northwestern University, Purdue University, the University of Michigan, Argonne National Laboratories, and the Universities of Illinois at Chicago and Urbana-Champaign, the NCLT will create education modules, aligned with national and state science education standards, for existing grade 7-12 curricula. These modules will be expanded for use in community college and undergraduate curricula, and will be combined to produce courses in nanotechnology[17,18].

In addition, the National Science Foundation's Nanoscale Undergraduate Education (NUE) program has provided funding for the development of more than 50 courses or course modules. This program has enabled the development of interdisciplinary nanotechnology courses for engineering and science majors[19-22], modules to fit into existing courses and laboratories[23-25], web-based instructional materials for nanotechnology[19,26], integration of nanotechnology research into undergraduate curricula[22,27], and development of new skills, such as operation of atomic force microscopes, that would facilitate employment[28]. While most NUE courses were designed for undergraduates in various science and engineering disciplines, several courses have been developed for undergraduates in non-technical majors[27,29,30]. The ethical and social issues, economic impact, leadership and entrepreneurship associated with nanotechnology are incorporated into many courses and modules[20,29-33].

There are also numerous new courses or modules for existing courses at other universities that have been developed with other funding. Several universities have grouped courses with nanoscience and nanotechnology content to produce certificates in nanotechnology. Drexel University and Pennsylvania State University have certificates in nanotechnology[34,35], Lehigh University has a graduate certificate in nanomaterials[36], George Mason University and the University of Massachusetts graduate certificate programs in nanotechnology and nanoscience[37,38]. Additional certificates have been proposed or currently approved at the Duke University[40], University of Pennsylvania, Georgia Institute of Technology, and the University of Kentucky. The last program is open to all undergraduates. Pennsylvania State University in collaboration with community colleges and other state colleges has developed an extensive program with A.S. and B.S. degrees in nanotechnology[39], while Dakota County Technical College is offering a A.A.S. in nanoscience technology[40]. Graduate degrees are available from the University of Texas Austin[41], Louisiana Technical University[42]. A growing list of institutions, both domestic and international has been compiled[43].

CHN Graduate-level Courses: Round I

Based on the courses available at other institutions, a three-credit graduate-level course in nanomanufacturing, offered simultaneously at the three universities and co-taught face-to-face by faculty from Northeastern University, the University of Massachusetts Lowell, and the University of New Hampshire, was proposed as the CHN's initial offering. (A three-credit course was not possible because of the asynchronous semester schedules of the three institutions.) What evolved, however, was a one-credit seminar course, "Introduction to High-rate, Template-based Nanomanufacturing," with six three-hour sessions offered biweekly from the beginning of UML's semester to the end of NEU's classes. With creativity, course numbers were assigned at each institution so that students could take this course for credit. A bus and lunch were offered as an inducement for students to take the 1.5-hour ride to the sister institutions.

Offered in spring 2005, the seminar course examines the issues associated with high rate template-based nanomanufacturing, including: technologies for nanoscale templates, high rate assembly of nanoelements and polymer systems, registration at the nanoscale, interfacing with biological systems, measurement of nanoelements, and molecular modeling. Environmental, regulatory, and ethical issues associated with new technologies are also addressed. The course presents not only the detailed information required for this subject, but also the basics needed for the cross-disciplinary student body (which includes social science and public health students as well as chemists, physicists, and engineers). The meeting dates are January 27, February 10, February 24, March 10, March 24, and April 7. Each meeting includes three 45-minute lectures with an additional 15 minutes for questions and a break. The course schedule is presented in Table 2 and selected topics are described in Table 3.

Table 2. Introduction to High-rate, Template-based Nanomanufacturing (Spring, 2005)

Date	Speaker	Topic
January 27 (NEU)	A. Busnaina	Overview of nanomanufacturing
	D. Papageorgiou	Basics of semiconductor/MEMS fabrication
	S. Somu / L. Chen	Nanoscale fabrication / Atomic probe microscopy
February 10 (UML)	J. Mead	Polymers and self-assembly of polymers
	C. Barry	Plastics processing at the nanoscale
	M. Ellenbecker / K. Geiser	Fundamental aspects of environmental and occupational health and safety as applied to nanomaterials
February 24 (UNH)	J. Harper	Nanotemplate fabrication using IBAD
	K. Pohl	Nanotemplates via strained metal interfaces
	G. Miller	Nanotemplates via self-assembling fullerenes and template functionalization chemistries
March 10 (NEU)	A. Busnaina	Control of contamination and defects
	G. Adams / N. Israeloff	Measuring the properties of nanoelements
	D. Tomanek*	Molecular modeling
March 24 (UML)	D. Kazmer	Modeling of polymer processing
	K. Marx	Issues in manufacturing biosensors
	J. Whitten	Measurement of forces for alignment
April 7 (UNH)	G. Miller	Using chemical forces for alignment
	H. Mayne	Modeling for alignment
	W. Kay / R. Sandler	Ethical and regulatory issues in emerging technologies

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Table 3. Selected Topics from Introduction to High-rate, Template-based Nanomanufacturing

Lecture	Topic Description
Jan. 27 A. Busnaina	Current nanotechnology research focuses on surface modification, matching molecules and "sockets" at the level of manipulating several to several hundred particles or molecules to be assembled into desirable configurations. Commercial scale-up can only be realized through high-rate assembly of nanoelements economically and using environmentally benign processes. This includes understanding what is essential for a rapid multi-step or reel-to-reel process, as well as for accelerated-life testing of nanoelements and defect-tolerance. To accomplish this, fundamental understanding of the interfacial behavior and forces required to assemble, detach, and transfer nanoelements, required for guided self-assembly at high rates and over large areas.
Jan. 27 S. Somu	Fabrication of nanoscale structures employing scanning electron microscope (SEM). An overview of the operation of SEM is covered. The lecture details each step involved in the fabrication process, fine tuning the steps to obtain 20-100 nm nanoscale structures and the difficulties encountered by a novice while employing the SEM to carry out nanolithography. Various available E-beam resists their unique properties that would be important for different fabrication techniques such as lift off and etching will be highlighted.
Feb. 10 J. Mead	A discussion of the structure and behavior of polymers, with a particular focus on block copolymers. This lecture includes basic morphology of single polymers, covering crystalline and amorphous structures and their associated thermal transitions; the effect of molecular weight on viscosity and properties; thermodynamics of mixing for polymer blends and the structure of block copolymers; and the morphology of block copolymers as a function of structure and methods to control the long range order of block copolymers.
Feb. 24 J. Harper	Ion beam assisted deposition is used to deposit thin films onto nanoscale patterned substrates. The deposition system consists of a high-vacuum chamber with two 3-inch diameter magnetron sputtering sources, one 3-cm diameter ion beam source, reactive gas capability for nitride and oxide deposition, substrate heating and rotation. The unique feature of this system is the combination of magnetron sputtering sources with a low-energy ion beam source that has a variable angle of incidence from normal to glancing angle onto the sample. The ion beam allows modification of thin film properties with known ion energy, flux and direction. Modification includes directional control of composition, topography (ripples) and crystallographic in-plane orientation.
Mar. 10 G. Adams	With the advent of micro- and nano-mechanical devices, there exists a need to develop methods for mechanical testing of materials at these small scales. Current methods include two classes - test beds consisting of fabricated devices integrated with testing instruments, and instruments such as micro- and nano-indenters in which the mechanical tester is separate from the material to be tested. The first class of mechanical testers has limitations since a sample of the material needs to be fabricated as part of the overall fabrication process, thus constraining the choice of materials to be compatible with the fabrication process. The second class of testers allows for better variability of materials, but is best suited to measure mechanical properties at the surface of the material.
Mar. 10 D. Tomanek	This lecture will introduce the basic computational tools used to understand the stability and equilibrium geometry of nanostructures, and to model their formation and disintegration as time-dependent processes. The first part of the lecture will address merits and limitations of techniques ranging from continuum modeling to bond-order interatomic potentials and ab initio electronic structure methods. I will show how these techniques provide an understanding of why and how the equilibrium geometry and stability of nanostructures may differ so much from bulk systems. The second part of the lecture will introduce molecular dynamics simulations and their use to understand key questions in the process of templated nanoassembly.
Mar. 24 D. Kazmer	A numerical simulation of injection molding and process variants are developed. A hybrid finite element/finite difference method is employed to model the temperature and pressure fields of the process using a non-isothermal compressible flow model. Simulation results for compact disc molding are compared with experimental observations using an optical grade of polycarbonate
Mar. 24 K. Marx	This talk will deal first with the general technical aspects of creating biosensors. Integration of the biological recognition element attached to a signal transduction mechanism capable of reading out analyte concentration will be described and some examples given. After a discussion of the overall goals of the antibody biosensor project and some of its potential clinical uses, specific technical hurdles that must be overcome in the development of the antibody biosensor will be presented.

This seminar course has proven popular with the graduate students, post-doctoral researchers, and faculty. While the enrollment was projected to be about 40 to 50 (based on the number of researchers associated with the CHN), the course has attracted 70 to 80 participants, including a large number of interested non-CHN participants, for the first two sessions. Many undergraduates expressed interest in attending, but most were prevented from enrolling because of course schedule conflicts. The contact between research groups has also provided opportunities to develop ties between graduate students and post-doctoral researchers in different parts of the project and check out the facilities at partner institutions. Moreover, as evidenced by the Center's seed proposals, faculty and post-doctoral researchers have been able to develop new research partnerships. The primary drawbacks have been the large time block required for participation in the course and snow-related cancellations that have already caused rescheduling of the Feb. 10 seminar to March 31.

The seminar will be evaluated using a web-based survey administered after the last seminar. This survey instrument will collect demographic data and feedback on the overarching objectives of the seminar. Although currently in revision, the tentative objectives include the participants ability to:

- Identify other members of the Center, particularly the principal researchers
- Comprehend the overall objectives of the Center for High-rate Nanomanufacturing
- Recognize the basic principles behind selected components of the Center's research
- See how their individual projects fit into the overall objectives of the Center
- Identify opportunities for future research and identify new research partners
- Grasp that nanomanufacturing is an interdisciplinary field
- Follow the vocabulary (jargon) of the other disciplines
- Judge potential environmental impacts of nanomanufacturing
- Consider the regulatory issues that may affect nanomanufacturing
- Reflect on the ethical ramifications that may result from the applications of nanotechnologies

Based on the current response, the seminar course will be offered again in spring 2007.

Graduate-level Courses: Round II

A three-credit senior elective/graduate course, "Introduction to Nanomanufacturing," has been scheduled as for fall 2005. The course will be offered jointly between the three universities, with one-fourth of the content assigned to each institution and the remaining fourth allotted for societal impact issues. Table 4 presents the preliminary content of this course.

Table 4. Preliminary Content of "Introduction to Nanomanufacturing"

Week	Topic	Week	Topic
1	Introduction	8	Nanoscale registration and alignment
2	Nanoscale characterization	9	Modeling 1
3	Basics of semiconductor fabrication/ Nanolithography	10	Measurement of material properties
4	Polymers/nanoscale polymer processing	11	Contamination and defect control
5	Handling of nanoparticulates	12	Ethical and regulatory issues
6	Dispersion of nanoparticulates	13	Economic assessment of processes
7	Advanced nanotemplates	14	Modeling 2

Each university will provide a separate course number for their students. The timing of the course and mode of delivery, however, are still under discussion. Most of the content will be delivered via the

Internet, but the universities are trying to schedule a common time to allow for interactions between the speakers and students.

In addition, the three universities are compiling lists of "nanocourses." The goals are that:

- Each university would be able to offer a nanoscale characterization course with similar or shared content.
- The graduate "Introduction to Nanomanufacturing" seminar course would be expanded to "Nanomanufacturing I" and "Nanomanufacturing II" graduate courses.
- A common graduate course or courses exploring societal impacts would be offered across all three universities.
- Students from any one of the three universities could enroll in specialized courses offered at one university. Discussions of an articulation agreement are scheduled to start in spring 2005.
- The three universities would develop a common graduate certificate track in nanomanufacturing.

Undergraduate-level Courses

Like the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (UIUC), the CHN has initially elected to add content to existing courses at the three institutions. NEU and UML faculty have been asked to submit proposals for the development of new or modification existing "nanomodules" for specific courses or sets of courses, whereas at UNH, a teaching post-doctoral researcher will create the modules. A portfolio of modules will be selected from the projects proposed at the three universities. The criteria for selection will include the type of course (with an emphasis on required freshman, sophomore, and junior courses), the novel nature of the new or modified module, and the portability of module to other courses and institutions. These modules will be incorporated into courses starting in fall 2005. After evaluation and modification, the modules, including instructional materials, will be shared across the three universities and with other institutions. Funding for the 2005-2006 and 2006-2007 academic years will emphasize expansion of the portfolio of modules and dissemination of the tested modules.

The capstone course will be initially offered as a "special projects" course for selected students. The CHN is currently collating potential projects with the skill sets needed for these projects. It is felt that many students will require extra training in order to develop successful projects. Since this training could be obtained from cooperative work experiences, undergraduate research experiences, or extra laboratory course work, matching the students with projects will require advanced planning for the students and faculty advisors. In addition, the logistics of cross-disciplinary, cross-University capstone projects are substantial. Since UML's College of Engineering is currently starting the implementation of a College-wide service learning based capstone, which will also include some students from the School of Health and Environment, this project may provide solutions for some of the logistics issues, such as scheduling and staffing, associated with the capstone projects. Therefore, the capstone project course will not be offered for several years.

The courses for non-science and non-engineering majors will be developed from course modules and existing Nanoscale Undergraduate Education (NUE) project at UML. Developed for face-to-face and on-line delivery, the current course, "Introduction to NanoEngineering," is being offered for the first time in spring 2005. Based on evaluations, this course will be offered again in fall 2005, and perhaps, spring 2006. Since on-line delivery will facilitate cross-university offerings of such courses, the Deans of Engineering (NEU and UML) and Engineering and Physical Sciences (UNH) will be asked to spearhead the development of an articulation agreement between the three Universities.

Evaluation

Under the direction of Eric Heller, Ed.D., the Research and Evaluation Group of the University of Massachusetts' Donahue Institute will conduct the evaluation of the courses. The evaluation will be organized around the questions of the extent to which the education activities of the CHN increase public awareness of the importance of science and technology to society and prepare undergraduate and graduate students in the participating institutions for careers in research as well as manufacturing related to nanotechnology. The assessment will be addressed from both an ongoing, formative approach and a summative perspective. Specific protocols including pre- and post-test instruments and telephone interviews will be developed to obtain data on the stated outcome measures. In addition to the web-based survey for the spring 2005 seminar course, a single survey instrument for the undergraduate modules and another for the 2005-2006 graduate courses are currently under development.

Conclusions

With the three-campus Center and advances in on-line education, opportunities for collaborative development of unique cross-disciplinary courses and cross-university capstone projects are possible. Three sets of nanomanufacturing courses will be offered to undergraduate students at all three campuses. The introductory course modules, designed to fit into existing freshmen science and engineering curricula, should prepare and motivate these students to become interested in the challenges associated with nanotechnology. Similar courses developed for non-science and non-engineering majors are intended to broaden the technological understanding of these students. Senior capstone design projects (in engineering) and senior thesis projects (in the sciences) are the basis for interdisciplinary, industry-sponsored projects in nanomanufacturing. Implementation of these course activities will begin in the spring semester of 2005, and results will be reported. The primary evaluation of this activities related to this education plan will be conducted by the Research and Evaluation Group of the University of Massachusetts, Amherst, Donahue Institute.

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