

**Nanoscience:
A Vehicle for a Goals-Oriented Science Education**

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Prepared by:
Shawn Stevens, University of Michigan, NCLT
Robert Cormia, Foothill De Anza Community College District
Vivian Dang, Boeing Corporation
Denise Drane, Northwestern University, NCLT
Nora Sabelli, SRI International
Joseph Krajcik, University of Michigan, NCLT
Michael Richey, Boeing Corporation.

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Summary

This project for Boeing's Learning Training and Development Engineering Group has looked at nanotechnology learning objectives and framework in postsecondary education and correlated them with industry needs, as identified by the Boeing Corporation and Foothill-De Anza (FHDA) Community College District. To do so, we developed and administered survey questionnaires for industry and academia. We then analyzed the responses to the questionnaires, together with prior materials science and engineering nanotechnology surveys conducted by FHDA to ascertain possible gaps in the preparation of a nanotechnology workforce. Boeing intends to make the study available electronically to three audiences: upper-division undergraduate and graduate faculty, lower-division and community college faculty, and precollege high school instructors.

We should emphasize both the preliminary nature and limited objectives of the work, so that our comments can be taken in context. We did not attempt to look into the basic science preparation that is fundamental for any nanoscience and nanoengineering preparation. Thus, the report has a short-term view on what is needed for a better integration of what exists currently, and does not deal with the long-term view of what nanoeducation should be. The list of competencies should be read with this caveat in mind.

The body of the report describes the surveys and the industry-derived competencies that drove the study and the analysis. Here we list our final conclusions and questions, and suggest areas for further inquiry.

Questions Regarding University, Community College, High School, and Industry Training and Education

1. Are colleges and universities preparing students with a solid foundation, but with "old skills," or just not preparing them well enough in general?

Faculty background is oriented toward nanoscience and engineering research, rather than engineering practice; thus students are better prepared to follow a research track than an industry track.

Even when an institution offers an engineering program, basic engineering courses either are not made readily available to nonengineering majors. Thus, nonengineers frequently lack exposure to fundamental engineering concepts. As a result, science majors are less prepared to work in a collaborative applied-science or technology environment after graduation.

Four-year colleges and universities are generally not preparing students well in the area of design—particularly in the design and engineering of high-performance materials and in the use of sophisticated simulation tools. This problem may be due to the lack of preparedness of incoming students; more likely, it is due to the lack of available tools and training in key areas such as design and simulation.

The faculty interviews suggest that the core concepts (big ideas) of nanoscience and nanotechnology (Stevens, Sutherland, Schank, & Krajcik, 2007) are not taught, emphasized, or integrated in science and engineering programs. In addition, courses' conceptual learning objectives are not shared or made obvious enough for students to ascertain the nature of the competencies expected of them or for prospective employers to ascertain the nature of expected student competencies.

2. *Are students being adequately prepared for the interdisciplinary nature of nanoscale science and engineering?*

The lack of preparedness in fundamental engineering concepts is especially true for students in the natural sciences. Students in these programs rarely, if ever, are educated in concepts such as design. Most science and engineering programs neglect to help students recognize the overlap of concepts across scientific disciplines.

Science and engineering are not well-integrated, leading to a strong disconnect between scientists and engineers involved in R&D in industry; that disconnect results in organizational deficits in rapid prototyping and scaling of nascent technology for manufacturing.

The background of departmental faculty is a strong determinant of the graduate and upper-division undergraduate courses offered in all disciplines. Thus, students across institutions do not receive a uniform set of knowledge and skills, instead receiving an education that likely to be *ad hoc* and institution-dependent.

Because faculty members chose the research track for their profession, they do not always have the requisite knowledge or experience to prepare students for success on the industry track. Nor does faculty engagement in industrial consulting seem to affect the way they prepare their students.

It is imperative that students be able to work collaboratively when they enter the workplace. Engineering programs currently make an effort to this end, but the basic sciences lag behind in this respect.

3. *Are 4-year institutions preparing undergraduates to enter the nanotechnology workplace?*

Few of the 4-year colleges and universities surveyed offer undergraduate courses in nanoscale science and technology that go beyond a basic survey. The courses that address nanoscale science and technology concepts in greater depth tend to be upper-division or graduate courses that may not be accessible to the average lower division undergraduate student. An academic “band gap” thus exists between undergraduate materials engineering and graduate nanoscience courses.

The capability models for materials science, when compared with those for nanotechnology, suggest that mastery of the fundamental concepts in a materials science program prepares students to advance into nanotechnology.

Recommendations: Science and Engineering Education

Relation between Science, engineering, and nanoscience education

A basic assumption of this report is the importance of basic science (physics, chemistry, and biology) as the foundation on which any nanoscience preparation must build. Both within basic science and engineering, it would be useful to have courses that cross traditional boundaries, and even more so between engineering and science.

Many of the concerns raised by this report will be lessened with increasing emphasis on the fundamental sciences, and with the introduction of design courses for science students.

An important “conundrum” is how to get cutting edge science and technology into courses for students with science backgrounds at only the first-or second-year level.

In several points the report mentions the need to give science students an introduction to engineering principles. Science undergraduates could be the best source for future nanotechnologists, and exposure to engineering and design principles would facilitate the training they will eventually need.

Nanoscience preparation for the workforce

We need more than short-term workshops for engineers and scientists who have already earned bachelor or advanced degrees in science and engineering. Changes must be made in formal science and engineering education programs.

More attention should be paid to how materials engineering programs prepare students for the workplace, and to deficiencies in that preparation. In particular, knowledge and skills relating to modeling, design, and engineering of nanostructured materials should be strengthened.

We suggest that a master's degree (8 to 10 courses) designed specifically to address these competencies may produce the best results.

Students should have more opportunities to experience “authentic learning” via “problem-based courses” or other mechanisms that emphasize collaboration and the application of general principles to broad technology areas.

Immersive laboratory experience addressing well-chosen broad application topics and well integrated with traditional courses will provide students with knowledge and skills they can easily transfer to the workplace.

Course offerings would benefit from a more detailed list of learning objectives, using a coherent framework such as knowledge, skills, and abilities (KSAs), or learning goals shared by academia and industry (Whitson, 1998).

Recommendations: Structural Issues

We need coherent, appropriate, knowledge and skill *conceptual assessments* based on an underlying framework, such as industry-derived KSAs or academia-derived learning goals

We need an infrastructure that enables the development of a distributed, emerging nanoscience and technology education community, similar to the one that has been funded for nanoscience research centers. Within such an infrastructure, electronic support mechanisms should be developed to bring academic and industry nanoscientists, nanoscience educators, learning scientists, and educators together to support joint activities, such as targeted workshops, innovative pedagogies and their dissemination, and regional equipment access centers.

Introduction, Goals, and Limitations of the Work

SRI International (SRI), the Boeing Corporation, Foothill-De Anza Community College District (FHDA), and the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) have conducted a limited, due-diligence study to look at learning outcomes relevant to postsecondary education and to correlate them with industry needs identified by Boeing and prior analyses of industry.

One part of the study consisted of analysis of work performed at Boeing related to the design, engineering, fabrication, and characterization of high-performance materials for advanced aircraft. The objective was to determine, as accurately as possible, key competencies (see the Example below) in four areas—design, engineering, fabrication, and characterization—and where, in a typical engineer’s training, those competencies were developed. That training could include academic training and professional experience or on-the-job training before or during employment at Boeing.

In parallel, FHDA and NCLT conducted an extensive analysis of courses and programs in materials science, polymers and composites, materials characterization, and fabrication. They analyzed approximately 400 courses from a cross-section of 4-year colleges and universities across the United States; they also assessed roughly 100 workshops for course objectives, learning outcomes, and identified competencies. They then organized the courses and workshops by discipline and categorized them in terms of competencies. This evaluation resulted in a broad list of primary learning outcomes and applicable competencies.

NCLT also conducted a similar course analysis of nanoscience- and nanotechnology-related courses at the NCLT institutions at Northwestern University, the University of Michigan (UM), Purdue University, the University of Illinois-Urbana-Champaign (UIUC), and the University of Illinois-Chicago (UIC). This analysis was used to supplement work FHDA had previously performed (FHDA & CACT, 2006). Approximately 150 formal courses and 15 noncredit short courses, workshops, or symposia were analyzed for course descriptions, learning outcomes, and competencies. This information was then compared with the nanotechnology competencies deemed relevant for the aerospace industry.

When relevant, courses were organized as course concentrations or course clusters. The course evaluations were supplemented with instructor interviews to gain more in-depth knowledge about select courses. In particular, faculty members were probed regarding their reasons for developing the course, the audience for which it was developed, the topics covered in the course, and the specific learning goals.

Example of the development of a competency

One can understand the scientific theory behind how instruments such as the scanning electron microscope (SEM), or the surface science instruments, auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), or electron spectroscopy for chemical analysis (ESCA) work. This type of understanding constitutes *knowledge* of materials characterization techniques. If practitioners can mount samples in the instruments, acquire good spectra, and interpret what the spectral data mean (e.g., what elements, molecules, compounds are present), they are considered to possess *skills* in relation to these instruments. However, using these instruments for problem solving and failure analysis requires going beyond the basic knowledge and skills associated with materials characterization. In fact, problem solving and failure analysis are considered *competencies*, and are capabilities practiced in context. To achieve these capabilities, practitioners must often integrate *knowledge* of materials (plastics, polymers, silicon) or devices (semiconductors, hard drives, etc.) with *skills* in the use of instrumentation and the practice of materials characterization. After a period of *practice*, practitioners become *competent* analysts and have the capability to solve a new problem with a reasonable amount of effort.

Observations and Summaries

I. Industry Survey

An online survey was developed to assess the scientific- and engineering-related competencies that aerospace engineers need for their jobs, and how they obtained them. The survey was administered to the participants of a materials characterization workshop given at Boeing. The results of this survey and of an independent survey FHDA conducted among San Francisco Bay Area industries served to identify a set of specific KSAs. A subset of the participants was interviewed to obtain more in-depth information. Engineers were asked what competencies were critical to their jobs, where they acquired those competencies (academia, prior professional experience, or their current jobs), their discipline, number of years of work experience, and number of jobs they had held.

The competency analysis was based on the KSA model (Whitston, 1998). The KSA model, a standard element in student learning outcomes, is derived from industrial psychology. The *knowledge* needed to do a job is derived principally from academic training, whereas the *skills* used to perform a job are learned through the repeated practice of a task. Once a task is learned well, it is considered a skill. We define *ability* as the product of knowledge and a skill, in the context of work. To prevent confusion with innate abilities, we use *capability* in the remainder of this document. A capability practiced in the context of work over a period of time can lead to competency. The notion of *competency* arises when abstract (formal) knowledge is combined with a work-related skill and the knowledge and understanding gained from a large experience (practice) base. Thus, knowledge and/or skill alone do not lead to competency. Competency allows practitioners to transfer their knowledge and skills, and apply them to solve new problems. For example, on completing medical school, a surgeon may have the capability to perform surgery, but is yet not deemed “competent” to do so. During her internship and residency, the surgeon gains experience and refines her skills until she has performed enough procedures that she can apply her knowledge and skills to deal with unforeseen complications. Likewise, pilots gain a competency through thousands of hours of flight time. In fact, the term “competency” has entered the language in that when speaking about competencies in instrument analysis, “flying time” is used in reference to experience.

Survey results. The results from the survey administered at a week-long nanotechnology workshop beginning October 4, 2006, at Boeing in Seattle indicated that engineers, in particular aerospace engineers, are involved in the design, engineering, manufacturing, and characterization of high-performance polymers and composite materials. The Web-based survey of 43 scientists and engineers (see Appendix A) suggested that four key areas defined their knowledge, skills, and capabilities: materials science, materials characterization, polymer and composite material fabrication and characterization, and manufacturing process engineering. In addition, the results from the survey found that the engineers developed and/or enhanced key competencies not only as a result of academic training, but also as a result of training and experience obtained during employment before joining the aerospace firm or through on-the-job training at Boeing. With respect to aerospace-related work performed at Boeing, competencies were identified in the following areas:

- Computer-aided design (CAD) and computer-aided manufacturing (CAM)
- Design and engineering (optimization of material structure with desired properties)
- Polymers and composite (characterization, engineering, and fabrication)
- High-performance alloys (characterization, engineering, and fabrication)
- Characterization (image, surface, bulk analysis, and physical properties)
- Characterization (quality assurance/quality control [QA/QC], problem solving, and failure analysis)
- Fabrication of polymer composite prototypes and completed panels

- Deep understanding of the aerospace industry and the development path at Boeing

Course analysis outcomes. More than 400 courses were identified that fit into the categories of materials science, polymers and composites, fabrication, and characterization. Complete engineering programs usually had three to five courses related to basic materials science, fabrication, and characterization, often including introductions to polymers, semiconductors, and basic characterization techniques. Additionally, approximately 200 courses were identified as relating to nanoscience and nanostructured materials.

Program analysis. Dozens of programs across the United States focus on materials science and engineering. Concentrations in these programs on fabrication and characterization are common, but advanced course work in engineering and design is much less common. As noted in earlier studies (FHDA & CACT, 2006), nanotechnology programs more often focus on developing knowledge and skills in basic nanotechnology, and especially in silicon fabrication and microelectromechanical systems (MEMS), and to a lesser extent, in other nanomaterials or devices such as carbon nanotubes. Few nanoscience programs offer dedicated coursework in nanocomposites, nanochemistry, ceramics, or high-performance alloys.

Academic needs. Both the analysis of courses and the interviews with faculty suggested that it is difficult to produce core skills in engineering and design related to material properties in a 4-year program. Advanced graduate work, which usually focuses on a single application, provides much better opportunities for building these capabilities. An increasingly large number of “hands-on” workshops are being offered in materials characterization. However, we found that they do not favor any particular materials focus. Without a solid foundation in engineering and recent on-the-job training in materials science, these workshops would probably not be effective in providing the advanced skills that Boeing and other industries desire.

Courses concentrating on nanoscale applications of materials science and engineering were found to be inconsistent across major 4-year institutions. A majority of the nanoscience related courses were upper level undergraduate or graduate-level courses. Only universities with large numbers of nanoscience researchers provided nanoscience courses that were broadly accessible to undergraduate students.

Limitations of the Survey

Our analysis of courses and programs in materials engineering, nanotechnology, and fabrication and manufacturing was limited by the information available in directory listings, and through search engine and Web navigation of academic Websites. As such, the analysis can be considered a “due-diligence” study to orient and justify future research and education work. In most cases, we were able to obtain at least a brief course description for the courses that we examined. More detailed learning outcomes were available in fewer cases. In almost all cases, courses were part of an existing program, rather than “free-standing” courses, allowing for more accurate “course clustering.”

Compiling a complete snapshot of the course offerings for all colleges and universities proved impossible for two reasons. First, although more than 100 hours of current (and archived) course analysis was performed, the number of colleges and universities is too great to thoroughly characterize the academic landscape. Instead, we sampled the top research institutions across the country. Because these institutions are well funded, they can be considered “best-case scenarios” when evaluating how colleges and universities deal with emerging science such as nanoscale science and engineering. Second, because of the time needed to collect comprehensive data, the programs themselves could change before a significant fraction of all U.S. programs were sampled. Even with these limitations, each of the analysts concluded that enough courses had been discovered to make reasonable generalizations about course goals and objectives and about learning outcomes for engineering programs.

The study was conducted with three audiences in mind: upper-division undergraduate and graduate faculty, lower division and community college faculty, and precollege high school instructors. We have also focused on preparation for engineering practice, as opposed to engineering research. The study complements the work of a prior National Science Foundation (NSF) workshop on nanoscience and nanotechnology learning goals, held by NCLT and SRI (Stevens, Schank, & Krajcik, 2007.)

II. Aerospace Engineering and Materials Course Analysis Summary

The number of courses and workshops dedicated to materials characterization of nanomaterials and to industrially important materials such as polymers and composites, has increased dramatically since FHDA's spring 2005 study. In addition, several new centers, such as the Center for Advanced Materials Characterization at the University of Oregon, provide seminars and hands-on training as well as workshops on the analysis of materials using sophisticated and cutting-edge analytical tools. These workshops provide opportunities for obtaining education from world-renowned experts in the analysis of materials and nanostructures in both noncredit and semicredit venues.

The recent evolution in engineering and manufacturing of materials for high-performance applications such as aerospace requires new, specialized knowledge in advanced engineering. Several universities now offer programs dedicated to engineering and manufacturing materials that are important in aerospace, as well as other industries: thin films and coatings, polymers, and ceramic materials. These programs build on foundational knowledge in engineering, and work to develop aspects of advanced engineering such as just-in-time, radio frequency identification, lean manufacturing, six-sigma (and total QA management), CAD or CAM of tooling, and information systems integration with business information systems.

Courses and workshops on the characterization of materials useful to the aerospace industry, including optical, organic, surface, structural, and physical properties of high-performance metals and alloys, ceramics and glasses, plastics, polymers, and composites systems, are now quite common. In addition to teaching the fundamentals of instrumentation, these courses include key aspects of approaching failure analysis, QA/QC, and materials characterization. Courses that focus on characterization of nanomaterials are less common, but still available at major academic research institutions. Hands-on training in the characterization of nanostructures is usually found only in graduate level courses or seminars at these institutions.

Interviews with aerospace engineers who participated in the web survey, as well as scientists and engineers working in industrial labs, suggest that on-the-job-training was their primary source of experience with real-world problem solving, which is critical for competency development. In summary, the number of courses and workshops whose learning outcomes support the aerospace industry and problem solving in engineering and manufacturing of high-performance materials is increasing, especially in regard to the ready accessibility of regional labs.

III. Summary and Analysis of Course Offerings

Materials Science and Engineering Competencies

Analyses of major course offerings in the six competencies identified in materials science and engineering—modeling and design, characterization and failure analysis, polymers and composites, and prototyping and fabrication—were used to determine student learning outcomes as knowledge, skills, and capabilities. These outcomes serve as a basis of comparison with the competencies determined from interviews of Boeing engineers, and from the subsequent analysis of gaps between academic offerings and industry requirements for further education.

Table 1 lists materials science and engineering courses, along with a summary description of the knowledge derived from the course and the learning outcomes (if stated).

Table 1. Materials Science and Engineering Course Analysis

Course	Description
Introduction to Materials	Overview of the discipline of materials, materials science, and materials engineering.
Structure of Materials	Structure of materials, polymers, crystals, glasses, metals, and structure property relationships.
Properties of Materials	Properties of materials, properties of material classes, structure property relationships, characterization of physical properties.
Mechanical Properties and Mechanical Behaviors of Materials	Mechanical properties of materials, engineering materials, design of materials for industrial applications.
Material Selection	Materials selection for industrial applications.
Engineering Materials	Introduction to the process and discipline of engineering materials.
Modeling and Simulation	Modeling and simulation of material properties, structure property relationships, engineering of materials to produce new materials.
Surface Metrology and Tribology	Characterization of surfaces, surface roughness, measuring and engineering surface properties, with primary applications in tribology (friction, lubrication, and wear).
Surfaces and Surface Properties	Understanding of surfaces, surface structure and properties, and surface processes, as related to structure property relationships reactions at surfaces, and subsequent processing (modification) of surfaces to enhance engineering applications, such as adhesion, bonding, and catalysis.
Thermodynamics and Kinetics	Thermodynamics of materials, phase diagrams and properties, and kinetics of materials.
Physics of Solids	Practice and knowledge in the discipline of thermal, electronic and semiconductor properties of metals, alloys, ceramics, glasses, and especially semiconductor materials.
Particulate Processing of Materials	Engineering methods of fabricating and processing particles for use in various engineering materials, especially composite materials.
Processing of Materials	Processing of materials in fabrication, materials engineering, and manufacturing. Preparation of basic materials (metals, alloys, polymers and plastics, ceramics, and glasses) for fabrication into more complex materials.
Micro- and Macro-processing	Processing of materials at micro-and macro-structural levels in materials engineering. More complex processing of basic materials (metals, alloys, polymers and plastics, ceramics and glasses) for engineering of structure property relationships for developing more complex materials.
Nanofabrication	Discipline of nanofabrication across a variety of materials, including carbon, polymers, metals and alloys, ceramics, and glasses, and most of all, silicon in the fabrication of devices ranging from nanotubes, to MEMS, to microsensors.

Table 1. Materials Science and Engineering Course Analysis (concluded)

Course	Description
Nanomaterials	Science and engineering, design and engineering, modeling and simulation, and fabrication of nanostructured materials, including carbon nanostructures (carbon nanotubes and multiwalled nanotubes), nanofibers and composites, metals and metal composite systems, ceramics and glasses (especially spin glasses), polymers and composites, and especially semiconductor materials. Nanomaterials can also include biological materials, such as DNA, RNA, and proteins, when used in templating and self-assembled systems.
Nanostructures	Science and engineering, design and engineering, modeling and simulation, and fabrication of nanostructured materials, including carbon nanostructures (CNT and MWNT), nanofibers and composites, metals and metal composite systems, and ceramics and glasses.
Characterization of Materials	Materials characterization, including failure analysis, QA/QC, process engineering support, with emphasis on image analysis; surface analysis; elemental, chemical, and molecular identification; and structural characterization. Emphasis on tools, which provide a complete picture of a material as required; optimizing structure property relationships; materials design and engineering; and development of high-performance materials.
Nanocharacterization	Characterization of nanomaterials and nanostructures, with emphasis on atomic, molecular, and crystalline structure of a material to support modeling and simulation, design and engineering, and process development of materials with novel structure/property relationships. Emphasis on more advanced and complicated analysis techniques, including high-energy microprobes and nanoprobe, electron and ion beams, and optical methods. Increased reliance on computer simulation of molecular structure and related properties.

As noted, the materials science programs of the NCLT institutions were compared in a different manner. The primary NCLT institutions are Northwestern, UM, Purdue, UIUC, and UIC. (UIC does not offer a degree in materials science.) The core courses of the programs were tabulated and categorized on the basis of course descriptions published in these universities' course catalogs (see Appendix B). The core courses represent those that all students complete regardless of their specialty or concentration. The core courses from each institution were then compared against a list of competencies FHDA generated (R. Cormia) (see Table 2)

The materials science electives listed in Appendix B make up a subset of the departmental higher level courses from which students select to form their concentration. Therefore, the courses listed here are restricted electives. For example, UM's program lists six courses, and students must choose three from that list. The department offers many more upper level courses as well, but they are free electives. Northwestern's program offers several concentrations from which students can choose. Each concentration consists of five upper-level courses. Once all required courses are taken into account, some but not all deficiencies are met by the programs in all of the schools.

Comparison of Materials Science and Engineering Programs.

The materials science and engineering (MSE) programs at the NCLT institutions meet most of the competencies FHDA described (FHDA & CACT, 2006), but study of thin films, surfaces, colloids, and particles is missing from the core of most programs. However, the institutions do uniformly include

kinetics/transfer phenomena as part of their programs. Although modeling and simulation were identified as important competencies, MSE programs do not assign these areas priorities. When they are in the curriculum, they are part of a course, not the focus. (The exception is UM’s program, MSE 489.) Therefore, this topic may be a good candidate for workshops or symposia.

Table 2. Materials Science Competencies

Knowledge and Concepts	Northwestern	UM	Purdue	UIUC
Structures of materials	MS 201	MSE 220, 250	MSE 230	MSE 201
Properties of materials	MS 201	MSE 220, 250	MSE 230	MSE 308, 304
Processing of materials	MS 201, 390	MSE 220	MSE 230	MSE 182
Performance of materials	MS 3332, 390	MSE 220, 250	MSE 230, 367	TAM 206
Material fabrication techniques		MSE 400		
Electronic, atomic, and molecular structure	MS 201		MSE 230	MSWE 182
Crystallography and crystal structure	MS 361	MSE 220	MSE 335, 350	MSE 405
Phase diagrams	MS314, 315	MSE 220	MSE 240	MSE 201, 402
Impurities and defects	MS 315, 316	MSE 220, 330	MSE230,382,502	TAM 206
Colloids and particles				
Metals and alloys	MS 201	MSE 420, 330	MSE 382	MSE 182
Semiconductors	MS 201, EE	MSE 250	MSE 370	MSE 182, 304
Glasses and ceramics	MS 201, 331	MSE 242	MSE 382	MSE 182
Carbon structures and fabrication	CHEM 210	MSE 220, 410		
Polymers and thermoplastics	MS 201	MSE 250	MSE 382	MSE 182, 403
Physics of solids (semiconduction)	MS 351	MSE 250		MSE 304
Surface and interface chemistry		MSE 242, 400		MSE 304
Thin films and deposition techniques		MSE 330	MSE 548	MSE 402
Kinetics/transfer phenomena	MS 315	MSE 335	MSE 340	MSE 402, 508
Modeling	MS 390	MSE 489	MSE 340, 505	

Note: Courses marked in gray are upper-level courses that students may choose, depending on their concentration.

Each program has its strengths and weaknesses. UM seems to have fewer laboratory requirements than the other institutions. Therefore, graduates have little characterization experience. Purdue, Northwestern, and UIUC appear to support characterization well.

Northwestern and UM have programs that integrate liberal arts (science) and engineering concentrations, which may help balance the science/engineering knowledge and experience. Northwestern has a materials science major in the Weinberg Liberal Arts College, which is usually a dual major with a science concentration in the college—physics and biology are especially encouraged.

UM’s Macromolecular Science and Engineering program bridges chemistry and engineering, which best supports the polymer knowledge and skill set. In this UM program, approximately one third of the core courses are cross-listed with the Chemistry Department, whereas most of the others are cross-listed with the MSE Department. Thus, this is an example of a very integrated program. However, the department offers only advanced degrees. Students can elect to follow a five-year program in which they earn a bachelor’s degree from another science or engineering department, and a master’s degree from Macromolecular Science and Engineering (see Appendix B for core courses and descriptions).

Materials Characterization Competencies

Materials characterization courses (see Table 3) were primarily analyzed using course descriptions. In a few cases, detailed course descriptions were available, and one course outline of record was obtained for this analysis.

Table 3. Materials Characterization Course Analysis

Imaga Analysis	Description
AFM imaging	Operation of an atomic force microscope (AFM), capability to acquire images from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization.
Optical imaging	Operation of an optical microscope, capability to acquire images from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization. All materials analysts should be proficient in optical microscopy.
SEM imaging	Operation of a scanning electron microscope (SEM), capability to acquire images from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization.
SPM imaging	In addition to AFM use, operation of the scanning probe microscopy (SPM) suite of tools expands the dimensions by which a surface can be characterized, especially lateral force microscopy (LFM) and magnetic force microscopy (MFM).
TEM imaging	Operation of a transmission electron microscope (TEM), capability to acquire images from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization.
Surface Analysis	
AES	Proficiency using Auger electron spectroscopy (AES), capability to acquire spectra from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization. Experience with depth profiles, elemental and chemical mapping, and secondary electron imaging.
XPS/ESCA	Proficiency using electron spectroscopy for chemical analysis (ESCA) and /X-ray photoelectron spectroscopy (XPS), capability to acquire spectra from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization. Experience with depth profiles, elemental and chemical mapping, and secondary electron imaging.
SIMS profiling	Proficiency using ESCA XPS, capability to acquire spectra from a variety of materials, and analysis and interpretation of data in the context of problem solving and materials characterization. Experience with depth profiles, elemental and chemical mapping, and secondary electron imaging.
Organic Analysis	Description
Image analysis	Proficiency using Fourier transform infrared spectroscopy (FITR), capability to acquire spectra from a variety of organic materials, and analysis and interpretation of data in the context of problem solving and materials characterization. Capability to integrate data with other organic analysis tools.
Raman spectroscopy	Proficiency using Raman spectroscopy, capability to acquire spectra from a variety of organic materials, and analysis and interpretation of data in the context of problem solving and materials characterization. Capability to integrate data with other organic analysis tools.
HPLC chromatography	Proficiency in all aspects of high-pressure liquid chromatography (HPLC), capability to acquire spectra from a variety of organic compounds and mixtures, and analysis and interpretation of data in the context of problem

	solving and materials characterization. Capability to integrate data with other organic analysis tools, with a strong emphasis on separation, identification, and quantification of complex mixtures of organic compounds, and excipients, from extraction of polymers and composites. Mass spectroscopy (MS) knowledge and skills related to LC/MS technology.
GLC	Proficiency in all aspects of gas-liquid chromatography (GLC), capability to acquire spectra from a variety of organic compounds and mixtures, and analysis and interpretation of data in the context of problem solving and materials characterization. Capability to integrate data with other organic analysis tools, with a strong emphasis on separation, identification, and quantification of complex mixtures of organic compounds, and excipients, from extraction of polymers and composites. MS knowledge and skills related to GLC/MS technology.
TGA	Thermo gravimetric analysis (TGA) of polymers to characterize polymers and composite systems, and identify both the thermal properties of polymer composite systems, as well as to help identify thermal response (and release of offgassing materials) especially for high-temperature applications.

Materials Characterization	Description
Crystallography	Proficiency in using X-ray diffraction (XRD)
Polymers and composites	Proficiency in characterizing polymers and composites, especially structure, morphology, and elemental and chemical composition. Emphasis on structure property relationships, adhesion, bonding, and failure analysis of laminate systems.
Metals and alloys	Proficiency in characterizing metals, alloys, and metal composite systems, especially structure, morphology, and elemental and chemical composition
Glasses and ceramics	Proficiency in characterizing glasses, ceramics, and ceramic composite systems, especially structure, morphology, and elemental and chemical composition.
Failure analysis	Proficiency in conducting failure analysis and problem solving, especially related to polymers, plastics, metals and alloys, in aerospace materials and applications.
Fracture mechanics	Proficiency in analyzing fractures, especially related to polymers, plastics, and composites, in aerospace materials and applications.
Physical properties, rheology, and viscosity	Physical properties measurements of plastics and polymers, especially rheology and viscosity.
Strength and deformation	Physical properties of plastics and polymers, especially strength and deformation.

Polymer Competencies

This analysis was derived from analysis of more than 50 courses from roughly a dozen institutions, three of which have formal programs in polymers. Thus, the summary in Table 4 provides a fairly detailed description of how 4-year institutions prepare students in polymer technology.

Table 4. Polymer Course Analysis

Course	Description
Plastics Technology	Overview of plastics science and technology.
Plastics and Elastomers	Science and technology of blended elastomers and plastics.
Basic Polymer Science	Science of synthesis and mechanics of polymer chemistry.
Composite Materials Technology	Overview of composite materials (applied technology.)
Injection Molding and Extrusion	Practice of injection molding and extrusion.
Advanced Polymer Processing	Advanced topics on polymer processing, especially applications.
Mold Design/Maintenance	Design and maintenance of molds and molding technology.
Industrial Blow Molding	Industrial technology for blow molded components.
Adhesive Bonding Technology	Bonding technology focusing on adhesion.
The Science of Adhesion	Science of adhesion, focusing on materials and physical chemistry.
Fracture Mechanics	Materials science of fracture mechanics.
Surface Engineering	Surface engineering, derivatization, adhesion enhancement.
Polymer Engineering	Industrial engineering of polymers.
Polymer Synthesis	Synthetic methods and chemistry of polymers.
Organic Chemistry of Polymers	Organic chemistry of polymers and plastics.
Polymer Chemistry, Chains and Solutions	Engineering of end-groups and functional groups in polymers.
Polymer Chemistry, Properties of Bulk Materials	Rheology and other physical properties of polymers,
Synthesis of High Polymers Laboratory	Synthetic reactions and production of high molecular weight polymers.
Polymer Characterization Laboratory and Analysis	Characterization of polymers, emphasis on chemistry and physical properties.
Optical Characterization of Polymers	Use of optical techniques in polymer characterization (microscopy, light scattering).
Surface Characterization of Polymers	Characterization of polymers, emphasis on surface chemistry.
Multiphase Materials and Composites	Developing complex polymers and composites with multiple phases, focusing on engineering of structure, morphology, and bonding to achieve desired application properties.
Polymer Nanotechnology	Developing complex structures with polymers, and polymer composite systems with nanoparticles, focusing on engineering of structure, morphology, and bonding to achieve desired application properties.
Industrial Project Management	Managing larger scale industrial projects, from modeling and simulation to design and engineering, to fabrication, testing, and final manufacturing.
Polymer Technology Tool Making	Design of tools and tooling apparatus for fabrication of specialized polymer and composite parts.

IV. Nanotechnology Competencies

The following nanotechnology capabilities were determined from course analysis of San Jose State University (SJSU), the University of California at Santa Cruz (UCSC), Stanford University, and

Pennsylvania State University, in addition to the prior FHDA study of nanotechnology (FHDA & CACT, 2006):

- Biotechnology
- Characterization
- Energy
- Informatics
- MEMS
- Nanoelectronics
- Nanofabrication
- Nanomaterials
- Semiconductors
- Thin films

The capability model for nanotechnology described below focuses only on those related to the high-performance materials used in the aerospace industry:

- Nanofabrication
- Characterization and modeling
- Surface chemistry and engineering
- MEMS/NEMS, sensors, micro- and nano-devices.

Appendix C lists nanoscience-related courses at Northwestern, UM, Purdue, UIC, and UIUC.

Nanofabrication Competency

Description. High-performance materials used for aerospace applications include aluminum alloys, traditional and carbon-carbon composite materials, and glasses and ceramics. Certain challenges are unique to fabricating nanomaterials. For example, special processing is required to form and control microstructured materials. These materials must retain their structure and properties when they are incorporated into larger subcomponents and are exposed to a variety of environments. For example, air and space frames must be able to withstand both very high temperatures, rapid transitions from cold to hot and hot to cold, and the thermal cycling that occurs in and around low earth orbit.

Microstructured materials fabrication differs from that for traditional materials in several ways. For example, greater precision is required to control factors, ranging from grain boundary size to very precise alloy composition. Another challenge in processing is controlling and enhancing bonding of both similar and dissimilar materials.

Analysis. Courses that focus on explaining the macroscopic properties of materials in terms of the microscopic and atomic level are generally part of an undergraduate materials science curriculum. It is also common for students to be introduced to microfabrication at the undergraduate level at universities with nanoscience and technology research programs. However, nanoscale fabrication is rarely addressed at the undergraduate level. When it is, the nanofabrication courses tend to focus on individual processes or product categories (e.g., micro- or nano-electronics, nanolithography, self-assembly). Only in rare cases are courses offered that focus on general micro- and nano-manufacturing practices.

The faculty interviews suggest that instructors are attempting to help students deal with the interdisciplinarity of fields such as nanotechnology. Instructors recognize that students rarely have the opportunity, nor are they required, to make connections across the disciplines; accordingly, they need help in doing so to be prepared for practice. Interdisciplinary skills include not only connecting scientific knowledge from different disciplines, but also communicating effectively with practitioners in other

fields. Engineering courses often seek to incorporate real-world scenarios by including team projects in the curriculum. These projects often require interdisciplinary teams to solve problems (we call these “problem-based courses”).

Characterization and Modeling (Measurement, Simulation, and Modeling) Capabilities

Description. Characterizing nanostructures is a critical step in developing new materials, processes, and stable manufacturing processes. Modeling structures to design novel properties into, or from, materials is integral to materials design. As modeling programs become more sophisticated, they also play an important role in the analysis for materials characterization. The FHDA survey of the nanotechnology industry indicated that nanomaterials characterization is a resource that many companies lacked (FHDA & CACT, 2006). In addition to internal development of modeling and characterization skills, commercial resources must be developed to support the chain of innovation, from R&D to sustained nanomanufacturing. Although many engineers possess a deep understanding of structure-property relationships for traditional materials, similar capabilities for high-performance materials (e.g., carbon-carbon, carbon-metal, ceramic composites) are currently rare in industry.

Characterization of nanostructures extends beyond traditional optical and SEM techniques, often requiring the use of ion beam, X-ray, and electron scattering to obtain structural information. Competencies for operating these tools and interpreting data require a deep knowledge of the materials themselves, as well as of how fabrication affects the observed properties. In addition to materials characterization competencies, problem solving for process optimization and failure analysis for physical properties optimization are necessary competencies.

Analysis. Materials science programs offer general laboratory courses that introduce students to the capabilities and limitations of various tools used for materials characterization. These courses tend to be general in their focus, rather than seeking to build capability specifically for nanoscale applications. Upper-level undergraduate and graduate level courses that focus on XRD and electron microscopy are the courses generally offered that apply to nanomaterials characterization. Although SPM is a driving force behind the progress of nanotechnology, its use is mentioned only in the survey courses; courses that focus on its use are conspicuously absent. Courses concentrating on modeling and simulation skills tend to be found in natural science departments. They tend to focus on modeling of organic (including biomolecules) or inorganic molecules. It is rare to find undergraduate courses that focus on materials characterization or modeling specifically relevant to nanoscale science and engineering.

Instructor interviews suggest that graduate and upper level undergraduate students can gain knowledge and skills regarding several materials characterization techniques. In particular, students learn about the capabilities and limitations of the instruments in order to choose the proper technique to address the concern at hand.

Surface Chemistry and Engineering Competencies

Description. A good materials analyst or scientist needs to possess deep knowledge of surfaces—what they are, how their properties differ from those in the bulk phase, what surface processes apply, and how to approach a material surface characterization problem. In aerospace, this knowledge includes an understanding of how surfaces are involved in sintering, adhesion, and control of grain boundary formation, as well as traditional measurement of surface tension and surface energy. In some applications, surface engineering is required to change the number and type of surface bonds, or to prepare a surface for processing to optimize bonding and adhesion.

Analysis. Courses that relate directly to surface science are relatively few. Undergraduate programs tend to offer only a single introductory course on surface science. Even graduate courses are generally limited in this respect. This finding is surprising because tribology is a traditional area of study, yet it is

still missing from many programs. One of the great design and engineering challenges of nanotechnology is dealing with the surface forces exhibited between nanoscale objects or between the objects and a surface. Therefore, this deficiency will have to be remedied to better prepare students of *all* levels.

MEMS/NEMS, Sensors, Micro- and Nano-Devices (Smalltech) Competencies

Description. The border between micro and nano, especially from a fabrication perspective, is often merely semantic. MEMS, NEMS and sensors are collectively described as “smalltech.” Microfabrication using silicon and carbon to create micromachines and other mechanical structures is a large part of modern automotive technology. As MEMS become integrated with information technology and networked, their functions and applications take on entirely new dimensions. In the future, a network of bioMEMS will monitor medical status and work in concert to deliver drugs, much as pacemakers deliver lifesaving support to the body. As a competency, design and engineering of MEMS promise to support new industries beyond automotive, telecommunications, and biomedical as information technology, networks, and intelligent micromachines converge.

Analysis. Courses that cover MEMS are more prevalent at 4-year institutions than courses pertaining to the other nanotechnology capabilities. Frequently, multiple courses relate to the theory of MEMS as well as the design, fabrication, materials, and processing of these devices. Courses that cover MEMS are often offered as upper-level undergraduate courses. However, it is more common for them to be offered as special topics and graduate level courses.

V. Overview of Nanotechnology Education

A review of nanotechnology programs in the United States today shows a rapidly evolving landscape. Just 3 years ago, nanotechnology programs were found only at well-funded National Nanotechnology Initiative (NNI) and National Institutes of Health centers. Penn State was a prime example, having garnered significant state and federal funding to develop a network of community colleges that funneled students into a cleanroom training center, graduating more than 100 students (technicians) a year. Similar programs at Dakota County Technical College in Minnesota, in coordination with the University of Minnesota, graduated their first cohort of 25 students this year. More recently, the University of Albany became a center for nanotechnology training and development. The university’s College of Nanoscale Science and Engineering was funded using a combination of significant state monies, which were matched with federal funding. Although California may appear to have lagged behind, UC Santa Barbara has a nanoscience center that coordinates with its chemistry and physics departments, and UC Berkeley has just opened a \$600 million nanofabrication center. Private universities, most notably Stanford University, are home to large NNI centers, including that university’s Center for Probing the Nanoscale and nanofabrication facility. Although few colleges and universities have developed accredited 4-year degrees in nanoscience or nanotechnology, a few institutions such as University of New South Wales are notable exceptions.

Challenges

Most colleges and universities with strong engineering programs have thus far elected to just add one or two courses that introduce students to the field of nanotechnology and the tools for characterizing nanoscale materials. Creating a 4-year degree in nanotechnology entails several challenges.

First, it is too early to see where the field is going, and offering a small number of courses allows a nascent program to grow organically as enrollment builds, and the direction of the field emerges. A potential solution to this challenge is the approach used by the MSE and Mechanical Engineering departments at Northwestern. Each department has a nanotechnology-related concentration that students may choose. The concentration involves a set of upper-level technical electives taken after a more traditional foundation of core courses has been completed.

Second, funding poses a particularly difficult problem for community colleges and many 4-year colleges, which must rely on grants to fund even the smallest efforts. Even wealthy schools such as Stanford must rely on NNI grants for the tens of millions of dollars required to run a program, and often on hundreds of millions of dollars in gifts from alumni to build the massive infrastructure to house the instrumentation and research facilities to support these programs.

In addition, nanotechnology and nanoscience are multidisciplinary, consisting of all disciplines of science at the nanoscale. Therefore, they extend beyond single departments (e.g., chemistry and physics), instead spanning entire colleges or divisions. In particular, it is necessary to create bridges between the science and engineering disciplines.

Results from the online survey of scientists and engineers who attended the materials characterization workshop at Boeing indicated that scientists felt that they lacked engineering knowledge and skills (e.g., design, fabrication), and that engineers believed that a stronger background in the basic sciences would be helpful. Competition for grants, faculty, and institutional politics make this hurdle the most vexing for many 4-year institutions. In an extreme example, Stanford offers more than 100 courses that touch on nanoscience, nanotechnology, nanoelectronics, MEMS, silicon fabrication, and characterization at the undergraduate and graduate levels, but still does not offer an organizing degree.

Perhaps the most significant challenge toward developing a pedagogically sound nanoscience program is developing bridges between faculty across the fields/divisions within a college, and determining how best to develop and offer courses to students who have diverse technical backgrounds in science and engineering. This is a particular challenge that we uncovered in our investigations. For instance, in the field of engineering alone, materials science and electrical engineering often have a completely different focus regarding nanoscience education. Our survey of courses and our interviews with faculty at a number of institutions indicated that few resources are available to help create the meaningful bridges in curriculum, programs, and most of all among faculty. Those bridges are needed to develop a multidisciplinary foundation for students that includes both science (chemistry and physics) and engineering (materials science, design, and fabrication).

This study has found that a combination of knowledge of polymers and composites, engineering principles integrated with manufacturing, and capabilities in characterization (including problem solving and failure analysis) provides the most value. Even with this daunting set of desired capabilities, a working knowledge of aerospace (material applications and product roadmaps) is an additional requirement for creating the most valuable workforce.

The challenges for Boeing are not unique. In the growing field of bioengineering, many 4-year institutions are scrambling to combine engineering degrees with one or more years of science (chemistry and biology) and internships in molecular engineering (synthetic biology), biomedical devices (engineering, development, and characterization), and nanobiotechnology (bioMEMS, Lab-on-Chip, and DNA microarray development). Without integration and cooperation between departments, students would be required to complete a dual undergraduate degree or a strong minor, and/or a master's degree in the complementary field, which together would be likely to take 5 to 6 years. However, developing a program with full-time faculty dedicated to the multidisciplinary preparation of the students, and applicability of their skills to the needs of the workforce remains a significant challenge for 2- and 4-year institutions.

Potential Solutions

Institutions of higher learning are working in different ways to meet the educational challenges posed by nanotechnology. The degree program offered by the University of New South Wales and the certificate program created by University of Minnesota and Dakota County Technical College illustrate forward thinking in terms of building multidisciplinary foundations. Other institutions, such as Northwestern, have

added nanotechnology-related concentrations to existing programs. Regional centers have begun to provide “authentic learning” opportunities for learners of all levels.

University of New South Wales. Although the bachelor of science in nanotechnology is a 4-year program that resides in the university’s MSE School, it is in fact interdisciplinary. A significant portion of the curriculum lies within the Schools of Physics, Chemistry, and Biochemistry, with some coursework also completed in the Schools of Biology and Mathematics. Thus, the program provides a balanced education. The emphasis on biology and biochemistry is rare in nanotechnology programs and concentrations.

In the first year, students take introductory courses in mathematics, physics, and chemistry designed to provide a solid foundation for all scientific disciplines. In addition, they take courses in introductory biology, materials science, and nanotechnology. In the second year, they continue to focus on the natural sciences, but take more specialized courses and foundational courses in materials science and nanotechnology. In the third year, students can choose from electives to gain a background in a range of nanotechnology-related topics (e.g., nanomaterials, solid-state physics, biodevices). In their final year, students take more electives and complete an independent research project that focuses on a single topic within nanotechnology.

The following links provide more information about the program:

<http://www.nanotech.unsw.edu.au/> and <http://www.nanotech.unsw.edu.au/future.html>

Northwestern University. Northwestern offers a bachelor’s degree in materials science and engineering or mechanical engineering, with a concentration in nanotechnology. In each of these programs, students receive a foundation in mathematics and natural sciences, as well as the respective engineering disciplines. In the latter portion of the curriculum, students complete technical electives that support a chosen concentration. The nanotechnology program in Mechanical Engineering focuses on MEMS/NEMS and sensors. In the Materials Science and Engineering Department, students can choose to concentrate on nanomaterials or surface science. This type of approach allows the institution to maintain flexibility and change rapidly as the field moves forward (see Appendix D for a list of courses).

Dakota Technical College and the University of Minnesota. The A.A.S. degree in nanoscience technology from Dakota Technical College also follows an interdisciplinary approach. Program implementation was funded by an Advanced Technological Education grant from NSF. The program is offered through a partnership with the University of Minnesota where students complete a capstone semester at the Nanofabrication Center, Materials Characterization Lab, and Nanoparticles/Biotechnology Labs. Twenty-five corporate partners play roles in the program, including serving on the advisory board, consulting on curriculum, and showing students opportunities in industry by providing guest lecturers and facility tours. The curriculum exposes students to a breadth of scientific concepts, introducing them to aspects of nanotechnology in fields as diverse as biotechnology, agriculture, and materials science. Thus, students are well-prepared for a working environment that requires interdisciplinary collaborations. The capstone semester provides students with hands-on technical experience that is coordinated with coursework to prepare them to successfully enter the workforce.

The following link provide more information about the program (see Appendix D for the curriculum):

<http://www.dctc.edu/prospStudents/programs/nanoTech.cfm>

Pennsylvania State University. The program at Penn State and its Center for Nanotechnology Education and Utilization employs a multidisciplinary approach at both the undergraduate and technician levels. This extensive collaborative program also involves institutions throughout the state (23 community colleges and 10 4-year institutions). The community colleges offer an A.A.S. degree in nanofabrication and manufacturing technology (NMT). Some offer other nanotechnology-related concentrations or degrees. At the 4-year institutions, students can earn baccalaureate degrees from a variety of departments. These programs have nanotechnology-related concentrations in the degree programs of the individual

disciplines. Many of the programs' curricula incorporate a nanofabrication manufacturing technology capstone semester, in which students are exposed to state-of-the-art equipment and hands-on techniques in Penn State's cleanroom facilities. This experience is coordinated with six courses (see below) to prepare students to enter the workforce. Credit from these courses can be applied toward an associate or baccalaureate degree. Alternatively, the capstone semester can be a stand-alone experience, with students earning an NMT Certificate.

The six-course capstone semester includes the following:

- E SC 211 Materials, Safety, and Equipment Overview for Nanofabrication
- E SC 212 Basic Nanofabrication Processes
- E SC 213 Materials in Nanotechnology
- E SC 214 Lithography for Nanofabrication
- E SC 215 Materials Modification in Nanofabrication
- E SC 216 Characterization, Testing of Nanofabricated Structures and Materials.

For further information, see <http://www.cneu.psu.edu/> and <http://www.cneu.psu.edu/edOverview.html>.

Nanotechnology at Other Institutions. Nanotechnology programs are being developed and implemented at many 2- and 4-year colleges and universities across the country. For example, Foothill College's Physical Science Division offers a nanotechnology certificate program, California's only approved program. Although the program is independent of the Chemistry and Engineering departments, faculty members from those departments teach some of program courses. The program includes the following 10 courses:

- Introduction to Nanotechnology
- Materials Science for Nanotechnology
- Materials Characterization for Nanotechnology
- Surfaces and Thin Films
- Semiconductors and Electronics
- Semiconductor Fabrication Techniques (lecture)
- Semiconductor Fabrication Techniques (laboratory)
- MEMS and Devices
- Nanobiotechnology
- Nanotechnology Projects

The certificate program follows the general approach of Penn State, and is coupled with an A.S. degree offering. Courses may be taught in conjunction with 4-year institutions including SJSU and UCSC. The certificate also includes smaller component emphasis in characterization, fabrication, semiconductors, nanoelectronics, and nanobiotechnology (offered with the Bioscience department). The goal of the certificate is to provide training for students who already have B.S. or M.S. degrees and are interested in a career change, as well as for transfer students and technicians.

UIUC's Center for Nanoscale Science and Technology is implementing a broad interdisciplinary nanotechnology curriculum. The curriculum will include a broad set of disciplines, including:

- Basic sciences—microbiology, molecular chemistry, mathematics, physics
- Engineering sciences—agriculture, biochemical, bioenvironmental, biomedical, electrical, materials, mechanical

- Information sciences—biocomputation, communications

Programs for Advanced Materials and Advanced Manufacturing

Little is currently offered in any venue to support building knowledge and skills related to advanced materials. The deficiency is of concern because this knowledge will soon become crucial in industries that extend beyond the aerospace industry. For example, polymer and carbon composite advanced materials promise to be critical aspects of progress in the automotive and energy industries. These materials would contribute to achieving ultralight automobiles and clean energy strategies. Increased attention to climate change, resource depletion, and energy independence has refocused interested on smaller, lighter modes of transportation, powered through a combination of electric hybrid and fuel cell technology. Electric vehicles, which have a much lower greenhouse gas (GHG) profile, offer the possibility of being "fueled" with domestic electricity. It is estimated that as many as 20% of U.S. automobiles could be powered by electricity without significant changes to our electrical infrastructure. However, conversion of half of our automobiles to electric/fuel cell, or gas electric hybrids would necessitate an increase in energy production, with an emphasis on clean energy, notably wind, as a source of that energy, according to the U.S. Department of Energy.

Wind energy, notably large 1-MW turbines or bigger, can support between 500 and 2,000 automobiles each, at an infrastructure cost of about \$1000 per car. "Fuel" from these turbines is more than competitive with gasoline (at current prices), and even at a fully amortized cost would be about \$0.10 per vehicle-mile. To gain efficiency, lighter cars can be built with high-performance and crash-resistant polymers reinforced with carbon composites. The wind turbines themselves incorporate carbon composite blades, which span over 1,000 meters in the largest offshore installations. It is estimated that between 10 and 20 million ultralight vehicles will be needed by 2020 to meet the combined needs of GHG reduction, energy independence, and air pollution relief.

VI. Questions

The future of the manufacture of advanced materials requires a workforce grounded in materials science and characterization; chemistry and chemical processing; and engineering modeling, design, and integrated manufacturing. The challenges of multidisciplinary training are not unique to the aerospace industry. For example, bioengineering faces similar challenges. Although a number of community colleges and 4-year institutions have developed and are developing interdisciplinary nanotechnology programs that integrate chemistry, physics, biology, and engineering, more often than not, 4-year institutions offer nanotechnology courses only as electives their science or engineering programs.

The challenge for educators and industry is to develop workers who can successfully enter a high-tech R&D and manufacturing economy and who have a solid foundation that will support their continued career development over 25 to 30 years. To facilitate this development and sustainability, that foundation should integrate the fundamentally different approaches that scientists and engineers take when solving problems. An integrated science and engineering approach that considers the unique structure and property relationships found at the nanoscale and is tailored to local industry (whether aerospace, bioengineering, or clean technology) may represent the best investment of training and education dollars. Supporting faculty and deans in these efforts by developing integrated curricula that can be more easily incorporated into science and engineering courses may also hasten the integration of nanoscience and nanoengineering. An analysis of energy and transportation needs, beyond aerospace, suggests that this integrated approach is needed soon, given the expected importance that high-performance materials will have on the next energy revolution.

1. *Are colleges and universities preparing students with a solid foundation, but with "old skills," or just not preparing them well enough in general?*

Four-year colleges and universities are generally not preparing students well in the area of design. Particularly lacking are the knowledge and skills for the design and engineering of high-performance materials, and in the use of more sophisticated simulation tools. The problem may be due to a lack of preparedness among incoming students; more likely is the lack of available tools and training in key areas such as design and simulation. The lack of student preparedness is especially true for students in the natural sciences. Students in these programs are rarely exposed to fundamental engineering concepts such as design or to the overlap of concepts across scientific disciplines. Part of the lack of exposure results because, although every postsecondary institution has natural science departments, most do not have engineering programs. Even when engineering programs do exist at an institution, basic engineering courses that would provide exposure to fundamental engineering concepts are usually not offered, or made readily available, to nonengineering majors. Moreover, faculty background appears to be more oriented toward nanoscience research, as opposed to engineering practice. Thus, they prepare students better for success in the basic academic research track than for applied research in industry.

Faculty interviews also suggested that the core concepts (big ideas) of nanoscience and nanotechnology (Stevens, Sutherland, Schank, and Krajcik, 2007) are not taught, emphasized, or integrated in science and engineering programs. Although at one time these concepts and skills were specialized and disciplinary, nanoscale science now spans multiple fields, creating a need for an integrated perspective. A focus on the core principles of nanoscience and their interdisciplinary nature also applies to high school education. The increasing number of students that follow “2 + 2 + 2”¹ programs makes this particularly important. If high schools, community colleges, and 4-year colleges and universities are not unified in their approach, these students will not be adequately prepared for the workforce.

2. *Are students being adequately prepared for the interdisciplinary nature of nanoscale science and engineering?*

Integration of science and engineering is often inadequate. This is especially true for science majors whose training usually ignores engineering principles. The deficiency is reflected in problems that scientists and engineers face in industry. For instance, many nanoscientists cannot develop solutions that integrate basic engineering skills and knowledge, leading to organizational deficits in rapid prototyping and scaling up of nascent technology into manufacturing. This was a key finding of the FHDA survey of nanotechnology, and has been validated in this study by the clustering observed for courses in science or engineering programs, with few cross-listings between the two. For instance, polymers and composites are key topics that may be found in chemistry, materials science, or materials engineering curricula, but they rarely take the form of a curriculum that thoroughly blends the polymer science and engineering disciplines and provides strong foundations in both areas.

In addition, it is imperative that students be able to work collaboratively when they enter the workplace, given that the development process usually requires an interdisciplinary team of scientists and engineers. Students should be prepared to deal competently with experts in the other fields so that they can ask the appropriate questions and specify the proper requirements to solve their R&D problems. We have not found this practice prevalent at universities or community colleges.

The background of departmental faculty is a strong determinant of the upper level undergraduate and graduate level courses that are offered in all disciplines. Thus, students across institutions are not prepared with a uniform set of knowledge and skills, instead receiving an education that is institution-dependent. In addition, because the faculty chose the research track for their profession, they lack the requisite knowledge or experience to prepare students for success on the industry-track. Their courses tend to be geared more to preparing students for success in the research track of the profession. Faculty engagement in industry consulting does not appear to change this pattern. A possible solution might be to address the

¹ 2 years in high school, 2 years at a community college, and then 2 years at a 4-year institution.

upper level undergraduate/graduate courses found in all departments. Perhaps at least a portion of these courses can be taught by or in collaboration with industry counterparts so that students will be exposed to concepts and skills that will support their success if they choose the industry path.

3. Are 4-year institutions preparing undergraduates to enter the nanotechnology workplace?

Few institutions offer undergraduate programs that focus on nanoscale science and engineering. The competency models for materials science as compared to nanotechnology suggests that when the fundamentals of a strong materials science program are grasped, students are ready to advance into nanotechnology. However, few of the 4-year colleges and universities surveyed offered undergraduate courses in nanoscale science and technology that went beyond a basic survey course. When courses are offered that provide more in-depth treatment of nanoscale science and technology concepts, they tend to be graduate courses that may not be accessible to the average undergraduate student. As such, an academic “band gap” exists between undergraduate materials engineering and graduate level courses. The gap might be filled by a series of approachable introductory and survey courses in nanotechnology that reorient the knowledge structure of an undergraduate student toward advanced topics in nanostructures, nanofabrication, and nanocharacterization. We discuss this possibility further in the recommendations.

Recommendations

To develop a forward-looking workforce with multiple competencies in design and engineering of nanostructures, nanofabrication techniques, and nanocharacterization, we need more than short-term workshops that provide training for engineers and scientists who already hold bachelor’s or advanced degrees. Fundamental changes must be made in formal science and engineering curricula. Greater attention needs to be paid to the deficiencies found in materials engineering programs and students. In particular, efforts should focus on strengthening their knowledge and skills in regard to modeling, design, and engineering of nanostructured materials. These skills should also be introduced into natural science programs to prepare students for the workforce more adequately.

Because these changes may prove to be beyond the means of a 4-year program, a master’s degree specifically designed to address these competencies may produce the best results. Such a program would likely be 2 years in length, would consist of 8 to 10 courses, and include a capstone project that integrated design and nanostructured engineering, fabrication, and characterization. Such a program would not only benefit aerospace, but also help address the critical changes that are looming for the automotive industry (i.e., development of techniques for high-volume manufacture of high-performance composite materials that are light-weight and strong and developed around aluminum frames).

All programs should provide more opportunities for students to experience “authentic learning.” Such learning can manifest in many different ways: a curriculum that focuses more on problem solving would offer more problem-based courses and require students to apply their knowledge to new situations while working in teams whose members’ different expertise will better prepare them for both the research or industry tracks of their professions; and an immersive laboratory experience that is well-integrated with traditional courses would provide students with knowledge and skills that can be easily transferred to the workplace.

Further Considerations

Assessment and Learning Goals

A larger set of grade 9 to 14 programs for the preparation of the workforce of the future must be developed. These programs should aim to build student knowledge and skills around the big ideas in nanoscience (Stevens, Sutherland, Schank, and Krajcik, 2007)

In addition, our course survey found no evidence of assessment beyond traditional written final exams. This deficiency negatively affects the nature of the evaluation of all education-related efforts, including those from NSF. In view of the practice-oriented and interdisciplinary nature of nanoscience, to move the field ahead at a faster pace, we suggest that a concerted effort is needed now to develop appropriate assessments that measure students' knowledge and understanding of interdisciplinary concepts, as well as identify both students' capability and skills, and their understanding of deep interdisciplinary concepts.

Ideally, these assessments should be designed for the three audiences we consider in this study—high school, including faculty; community colleges; and universities. In addition, the learning goals developed in parallel with the study should be considered in terms of assessment.

Infrastructure

The disparity we found among courses with similar labels suggests that course labels are not sufficient descriptors. In addressing the need to use a more detailed set of labels to facilitate transfer among programs, we have considered two sets of labels that could offer such a solution: industry-derived KSAs and academic-derived learning goals.

Furthermore, we have been impressed with the infrastructure that NSF supports for the nanoscience and technology research centers (NNIN), including an education portal. We suggest that unless a similar infrastructure is developed for nanoscience and technology education, *both* the education efforts of individual faculty and of the faculty associated with research centers will suffer. Without a framework that helps situate learning goals, KSAs, and course offerings with respect to each other, the education-oriented efforts will inevitably result in duplication of efforts as institutions work to develop many independent and partial courses (Whitson, 1998).

The excellent work of the NNIN and its education portal and the contributions of NCLT to the development of a nanoscience education knowledge base offer a model. However, neither group has the mandate or the resources to develop such an infrastructure. For example, developing appropriate, quality assessments requires sustained collaboration among learning, assessment, and nanoscience specialists that cannot be achieved with small budgets. In a similar vein, although a portal can be developed with limited funds, its longer-term maintenance, upgrade, and support for efficient connection among and use of resources requires major, sustained funding.

References

FHDA & CACT. (2006). *Nanosurvey final report*. Foothill-De Anza Community College Center for Applied Competitive Technology, (Chancellor's Office) Document available by request.

Stevens, S. Y., Sutherland, L., Schank, P., & Krajcik, J., (2007) *The big ideas in nanoscience*. Available from http://hice.org/PDFs/Big_Ideas_of_Nanoscience-20feb07.pdf

Whitston, K. (1998). Key skills and curriculum reform. *Studies in Higher Education*, 23(3), 307-319.

Appendix A. Summary of the industry survey data

The survey had 43 total respondents, including representatives of 14 companies, 4 government national labs, and 2 universities. Approximately half were Ph.D. scientists or engineers, and about one-third had master's degrees. Nearly half of the respondents had a background in chemistry or chemical engineering.

The distribution of needed competencies and specific knowledge is shown in Table A-1.

Table A-1. Distribution of Competency Needs

Competency	Number Surveyed who Believe the Competency to Be Important
Characterization	34
Materials science	31
Fabrication	31
Modeling and simulation	22
Electronics	14
Devices (MEMS, etc.)	12

The survey highlighted the need for more authentic training. Respondents believed that training in the context of work that is realistic and authentic (i.e., beyond scenario-based learning) would better prepare students for the workforce. Approximately 75% of respondents wanted to have more personal knowledge about nanotechnology; however, what specific nanoscience knowledge was needed was not asked.

Respondents suggested a range of science courses that would be useful to their practice; some are foundational, and some are specific to the respondent's field of practice:

- Quantum physics
- Colloid science
- Characterization
- Polymer chemistry
- Mathematics/modeling
- Mathematic/statistics
- Aerospace operations and logistics
- Specific training in AFM, SEM, and TEM
- A refresher course in chemistry

Engineering courses to improve foundational and applied knowledge and skills were more germane to aerospace:

- Aerospace and aircraft requirements
- Aircraft composite materials use
- Mechanical, electrical, and computing skills
- Nanomechanics and mechanical testing

- Overview of MEMS and integrated circuit design.

How Do these Survey Results Compare with Prior Survey Results?

FHDA's work in summer 2005 suggested that nanotechnology as now practiced is concentrated into the following clusters of competencies:

- Characterization
- Modeling and simulation
- Fabrication
- Semiconductors and electronics
- MEMS and sensors
- Bionanotechnology

Our survey indicated the importance of a materials science foundation in all of the six competencies. When respondents were asked which knowledge was most key and which was most lacking in employees working in technology fields, they ranked materials science highest. Second, scientists indicated they often lacked key engineering skills, such as modeling, simulation, design, and building prototypes. However, this deficit was not identified by the respondents of the current survey at Boeing; almost 75% indicated that they perform materials-science related activities. Given the nature and location of the workshop, it is not surprising that this audience was focused on polymers and composites, with some focus on metal and ceramic materials, and minimal focus on semiconductors and electronics.

Strikingly, 75% of respondents worked in one or more of the concentrations noted in the following sentence. Skilled workers who are able to perform characterization, modeling and simulation, and fabrication are quite rare. However, given that the respondents appeared to be a very skilled group, they probably seek more advanced and specific training, rather than general courses in nanotechnology.

Additional knowledge about aerospace may be harder to find, especially courses that focus on the design, engineering, and characterization of composite materials for aerospace, on failure analysis, and on the logistics of materials use in aerospace. Courses in mechanical testing may be found in materials science; however, nanomechanical testing is quite specific.

Recommendations

For a follow-up voice survey of industry respondents, we suggest the following questions (See [IndustrySurveyData.xls](#) for raw data)

1. Identify the respondents again: What is your field—chemistry or engineering, fabrication or characterization? What degree do you hold—M.S. or Ph.D.? Are you a manager? If so, how big is your group?
2. How many years of experience do you have? Please compare academic training versus OJT.
3. Were you hired because of your KSAs specific to the aerospace job, or were your KSAs good enough to hire you, with the assumption that they would help you solve specific aerospace work problems through OJT?
4. Where did you acquire the specific competencies for your work—from research (M.S./Ph.D.), education, or primarily from OJT? What specific work or education got you where you are?
5. What knowledge and skill gaps do you have? What specific competency do you need in characterization or fabrication? What is driving that need?
6. What problems do you typically address—failure analysis, characterization, design, simulation, engineering; for what types of material; and using which specific techniques?
7. Have you thought about workshops for learning skills?

8. What is your specific interest in nanotechnology?
9. Do you manage or direct a technician?
10. If so, what work does he or she do to support you?

Appendix B. The Macromolecular Science and Engineering Program at The University of Michigan

The UM courses were collected as an example of an integrated program in which approximately half of the courses are cross-listed in the Chemistry department and the other half cross-listed in the MSE department. The core courses from the program are listed below.

Table B2. MSEP course description

Course Name	Course Number	Course Equivalent	Course Description
Physical Chemistry of Macromolecules	MacroSE 535	Chem 535	Thermodynamics of mixtures, the Flory-Huggins theory of polymer solutions, more modern theories of polymer solutions, the size and shape of macromolecular chains in solution and in bulk, rubber elasticity, polymer adsorption behavior, and polymer diffusion and scaling theories.
Laboratory in Macromolecular Chemistry	MacroSE 536	Chem 536	Experimental methods for the study of macromolecular materials in solution and in bulk state.
Organic Chemistry of Macromolecules	MacroSE 538	Chem 538	The preparation, reactions, and properties of high molecular weight polymeric materials of both natural and synthetic origin.
Polymeric Materials	MacroSE 412	MSE 412	The synthesis, characterization, microstructure, rheology and properties of polymer materials. Polymers in solution and in the liquid-crystalline, crystalline, and glassy states. Engineering and design properties, including viscoelasticity, yielding, and fracture. Forming and processing methods.
Applied Polymer Processing	MacroSE 414	MSE 414	Theory and practice of polymer melt processing. Non-Newtonian flow; extrusion, injection, and molding operations; fiber, film, and rubber processing; kinetics of solidification; mechanical orientation; product characterization; structure-property relations
Polymer Physics	MacroSE 512	MSE 512	Structure and properties of polymers as related to their composition, annealing, and mechanical treatments. Topics include creep, stress relaxation, dynamic mechanical properties, viscoelasticity, transitions, fracture, impact response, dielectric properties, permeation, and morphology
Theory of Linear Viscoelasticity	MacroSE 517	ME 517 AM 517	Constitutive equation for linear small strain viscoelastic response; constant rate and sinusoidal responses; time- and frequency-dependent material properties; energy dissipation; structural applications, including axial loading, bending, torsion; three dimensional response, thermo-viscoelasticity, correspondence principle, Laplace transform, and numerical solution methods
Composite Materials	MacroSE	MSE 514	Behavior, processing, and design of

	514		composite materials, especially fiber composites. Emphasis is on the chemical and physical processes currently employed and expected to guide the future development of the technology
Mechanical Behavior of Solid Polymeric Materials	MacroSE 515	MSE 515	Mechanical behavior of polymers from linear viscoelastic to yield and fracture. Specific topics include dynamic-mechanical relaxations, creep, yielding, crazing, fatigue, and fracture mechanics. Materials include toughened plastics, polymer alloys and blends, and composite materials. Structured design with plastics is also considered.

For more information and complete data, see [MacromolecularS&E-UM.xls](#).

Appendix C. Courses for Competency Analysis

NCLT Materials Science and Engineering Programs

We compared the materials science programs of the NCLT institutions, with the core courses tabulated and categorized on the basis of the course descriptions as published in course catalogs (see the spreadsheet). The core courses represent the courses that all students complete, regardless of their specialty. The core courses from each institution were then compared against a list of competencies generated by Robert Cormia and FHDA.

The materials science electives listed in a separate spreadsheet represent a subset of the departmental higher-level courses from which students select to form their concentration. For example, students must choose three courses from the six UM courses listed. The department offers many more upper-level courses, but they are true electives. The ones listed are only partially free electives. Explanations for each institution are contained in the spreadsheet, adjacent to the course entry listed. If not noted, the courses are higher level electives. In all cases, some but not all deficiencies in prior knowledge are met when the selection of electives is considered.

See the [NCLT-MSE-competency.xls](#) for NCLT data.

See the [FHDA-competency-course-list](#) for NCLT data

Appendix D. Nano-related courses

Nano-related courses were collected from the NCLT institutions: Northwestern, UM, Purdue, UIC, and UIUC. The courses were selected on the basis of the course descriptions in each institution's course catalog. When available, syllabi, course outlines, and learning goals/outcomes were also used in the evaluation.

Criteria for course selection of nano-related courses were the following:

- “Nano” appears in the course title or description.
- The course is about nanoscale phenomena or devotes a significant portion to those phenomena (e.g., physical basis of molecular recognition, macromolecular structure, piezoelectric).
- Solid-state chemistry/physics.
- Chemistry/structure/properties of surfaces.
- Molecular recognition (e.g., how drugs work, how matter interacts).
- Techniques for measuring nanoscale objects (electron microscopy, biomolecular NMR spectroscopy, XRD, etc.)
- Advanced inorganic chemistry—materials related (e.g., crystal field theory, electronic structure)
- Microelectronics (e.g., MEMS).
- Departments:
 - All engineering, but especially materials, mechanical, and biomedical science
 - Chemistry
 - Physics
 - Biophysics
 - Biochemistry
 - Macromolecular science (UM).

Noncredit Education

Short courses and workshops sponsored by research centers at the various institutions were also collected. They are listed in the worksheet labeled “informal.”

See the [NCLT-nano-course-list.xls](#) for data.

The following URLs provide additional information copied from teach organization Web site:

Northwestern University Course Descriptions and Course Schedules

- Materials Science course schedule
http://aquavite.northwestern.edu/courseplanner/courseplan-courses.cgi?acadyear=2006-2007&dept_id=750&school_id=700
- Course descriptions (current quarter only)
http://aquavite.northwestern.edu/cdesc/course-list.cgi?quarter=W06&dept_id=750&school_id=700&pagetype=c
- Mechanical Engineering: who takes it, description, detailed syllabus, instructor
<http://www.mech.northwestern.edu/dept/undergrad/index.html>
- Electrical Engineering and Computer Science undergraduate manual (no unified course descriptions yet)
http://www.eecs.northwestern.edu/docs/UNDERGRAD_final.pdf
- Electrical Engineering & Computer Science course schedule
<http://www.eecs.northwestern.edu/academics/course/06-07-courses/>

- Chemical Engineering catalog and course schedule
http://www.chem-biol-eng.northwestern.edu/ugradpgm/courses/courses_06-07.pdf

University of Michigan Course Descriptions

- Biophysics Research Division
<http://www.umich.edu/~biophys/ugrad/academic.html>
- Chemistry (course guide only)
<http://www.lsa.umich.edu/cg/>
- Physics
<http://www.lsa.umich.edu/physics/courses/>
- Materials Science & Engineering
<http://www.mse.engin.umich.edu/undergraduate/courses>
- Mechanical Engineering
http://me.engin.umich.edu/current/course_information.shtml
- Electrical Engineering and Computer Science
<http://www.eecs.umich.edu/courses/index.html>

University of Illinois-Chicago Course Descriptions

- Chemistry
<http://www.uic.edu/ucat/courses/previous/chemucat.html>
- Physics
<http://physicsweb.phy.uic.edu/undergraduate/ugcourses.asp>
- Bioengineering
<http://www.uic.edu/ucat/courses/BIOE>
- Chemical Engineering
<http://www.uic.edu/ucat/courses/CHE>
- Civil & Materials Engineering
<http://www.uic.edu/ucat/courses/CME>
- Electrical & Computer Engineering
http://www.ece.uic.edu/Undergraduate/uGrad_Course.html

Purdue University Course Descriptions

- Assessment of Nanomaterials in the Environment
<http://www.ydae.purdue.edu/ANE/courses.htm>
- Electrical & Computer Engineering
<http://www.courses.purdue.edu/cgi-bin/relay.exe/query?qid=courseOfferingList&abbreviation=ECE&academicInitiative=puWestLafayetteTrdn&session=2007Spr>
- Materials Science Engineering
<http://www.courses.purdue.edu/cgi-bin/relay.exe/query?qid=courseOfferingList&abbreviation=MSE&academicInitiative=puWestLafayetteTrdn&session=2007Spr>
- Biomedical Engineering
<http://www.courses.purdue.edu/cgi-bin/relay.exe/query?qid=courseOfferingList&abbreviation=BME&academicInitiative=puWestLafayetteTrdn&session=2007Spr>

The following table sets forth courses listed in some form on <http://www.nanoed.org/>, an NCL- affiliated website, as of January 2007.

Table C1. Courses Listed by The Nanoed website

Course	Instructor	Institution
Undergraduate level		
Carbon Nanotubes	Meyya Meyyappan	NASA Ames
Fundamentals of Nanoelectronics	Supriyo Datta	Purdue
Introductory Physics of Materials	Mark C. Hersam	Northwestern
Introduction to Nanotechnology	Meyya Meyyappan	NASA Ames
Nanoscale Patterning and Systems	Teri W. Odom	Northwestern
Nanomaterials	Mark C. Hersam	Northwestern
Nanoscale Patterning	Teri W. Odom	Northwestern
Science and Technology at the Nanoscale	Teri W. Odom	Northwestern
Nanoscience and Nanotechnology	Venkat Chandrasekhar	Northwestern
Graduate level		
Advanced Physics Of Materials	Mark C. Hersam	Northwestern
Advanced VLSI Devices	Mark Lundstrom	Purdue
Electronic Transport in Semiconductors	Mark Lundstrom	Purdue
Nanophotonics	Vlad Shalaev	Purdue
Quantum Phenomena: Atom to Transistor	Supriyo Datta	Purdue
Science and Technology at the Nanoscale	Teri W. Odom	Northwestern
Nano Units		
Introduction to Scanning Probe Microscopy	Lincoln J. Lauhon	Northwestern
Introduction to Nanometer Scale Science and Technology	Mark C. Hersam	Northwestern

The nano-related centers and facilities located at the NCLT institutions, as identified through web searching, are listed below; information was copied from each organization website.

NORTHWESTERN UNIVERSITY

Nano related Facilities

Institute for nanotechnology

At the forefront of this new scientific frontier, the Institute for Nanotechnology was established as an umbrella organization for the multimillion-dollar nanotechnology research efforts at Northwestern University. The role of the Institute is to support meaningful efforts in nanotechnology, house state-of-the-art nanomaterials characterization facilities, and nucleate individual and group efforts aimed at addressing and solving key problems in nanotechnology.

Currently comprised of two major interdisciplinary research centers and a celebrated group of award-winning faculty and students, the Institute positions Northwestern University and its partners in academia, industry, and national laboratories as leaders in this exciting field.

Nanoscale Science and Engineering Center (NSEC) for Integrated Nanopatterning and Detection Technologies

(Northwestern University, University of Chicago, University of Illinois at Urbana-Champaign, and Argonne National Laboratory)

Center research is driven by a vision to develop innovative biological and chemical detection systems capable of revolutionizing a variety of fields. Genuine medical benefits are now emerging as direct products of the center research, including detection techniques for markers associated with diseases such as Alzheimer's disease and prostate cancer. These detection techniques are bringing advances in sensitivity, speed, ease of use, and cost over existing methods, providing broader societal impact of a type and degree that is impressive.

Center members represent a broad spectrum of disciplines including biochemistry, molecular biology, cell biology, biomedical engineering, bioethics, chemical and biological engineering, chemistry, electrical and computer engineering, materials science and engineering, mechanical engineering, neurobiology and physiology, physics and biophysics, and medicine.

The Center has developed an innovative and comprehensive educational outreach program that impacts the traditional classroom as well as informal science education. Partnerships have been developed with the Museum of Science and Industry and numerous Chicago-area high schools and universities that have enriched these educational opportunities.

Nanoscale Interdisciplinary Research Team (NIRT) for Multiscale Modeling and Catalysis for Green Chemistry and Engineering

NIAID-Specific Detection of HIV Targets by Gold Nanoparticle Probes

(Northwestern University & Johns Hopkins University)

Center for Nanofabrication and Molecular Self-Assembly

UNIVERSITY OF ILLINOIS—URBANA-CHAMPAIGN

Nano-related Facilities

Micro and Nanotechnology Laboratory (MNTL)

Photonics + Nanotechnology + Microelectronics + Biotechnology

Research Areas—Optoelectronics and Photonic Systems, Microelectronics for Wireless Communications, Microelectromechanical Systems, and Nanobiosystems

Cleanroom available for use

Equipment- <http://www.micro.uiuc.edu/Equipment.htm>

Center for Nanoscale Science and Technology (CNST)

CNST envisions seamless integration of the research from materials to devices to systems and applications.

- Interdisciplinary curriculum unique to University of Illinois
- Industrial alliances and technology transfer
- Potential for local and state economic development activities
- A major magnet to recruit and retain faculty
- Springboard for future interdisciplinary proposals
- Maintain world leadership and College/Department rankings
- Establish UI as the premier institution in nanotechnology.

CNST commits to contributing towards the goals set forth by the Illinois Board for Higher Education. **CNST takes on the challenge for the development of a nanoscale science and technology curriculum** unique to the University of Illinois. The curriculum will provide students with a broad interdisciplinary understanding of the nanotechnology as it applies to basic and applied research. The students with this unique curriculum will gain knowledge, develop skills, and appreciate the role nanotechnology is likely to play in shaping our future. CNST is leading the effort in preparing our students today for tomorrow's challenges.

Table D-1. Curriculum Characterization

Basic Sciences	Microbiology, molecular chemistry, mathematics, physics
Engineering Sciences	Agriculture, biochemical, bioenvironmental, biomedical, electrical, materials, mechanical
Information Sciences	Bio-computation, communications

The Materials Computation Center

As the Computational Materials Science discipline affects all fields of Science and Engineering, the Materials Computation Center (MCC) is actively developing powerful, leading-edge tools to analyze and predict the properties of materials.

The Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)

Research in the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS) addresses a central problem in the development of nanotechnology: how to assemble structures at sizes smaller than can be seen (or transduced) and manipulated (or transcribed). Making three-dimensional, nanoscale devices and systems from millions to trillions of different types of molecules is incredibly difficult. The Center's goal is to develop a reliable, robust and cost-effective nanomanufacturing system to make nanostructures from multiple materials. This technology will allow advancements and discoveries in nanoscience to move from the laboratory to production.

The Nano-CEMMS Center is a partnership of the University of Illinois, the California Institute of Technology, and North Carolina Agricultural and Technological State University. Each partner offers unique facilities, eminent scholars and financial resources to support the Center's research.

UNIVERSITY OF MICHIGAN

Nano related Facilities

National Nanotechnology Infrastructure Network (NNIN)

Michigan Nanofabrication Facility (MNF)

Electron Microbeam Analysis Laboratory (EMAL)

Hannawalt X-Ray Diffraction Laboratory

Michigan Ion Beam Surface Modification and Analysis Laboratory (MIBL)

It contains five process bays (silicon lithography/diffusion, silicon LPCVD, compound semiconductor devices, thin-film deposition, and dry etching) plus five connected rooms for e-beam lithography, metrology, and III-V materials growth. In-house metrology includes SEM, spectroscopic ellipsometry, Hall, AFM, and profilometry.

Further characterization facilities are available through the UM Electron Microbeam Analysis Laboratory (EMAL) and the Hannawalt X-Ray Diffraction Laboratory, which include FE-SEM, Auger, XPS, TEM, and high-resolution X-ray diffraction and grazing-incidence X-ray reflectometry. In addition to EMAL, the Michigan Ion Beam Surface Modification and Analysis Laboratory (MIBL) provides additional metrology capabilities such as Rutherford Backscatter Spectrometry, Nuclear Reaction Analysis and Elastic Recoil Detection. UM NNIN staff will assist users with this full battery of characterization tools.

The Michigan Nanotechnology Institute for Medicine and Biological Sciences (M-NIMBS)

M-NIMBS is a multidisciplinary team of chemists, physicists, engineers, pharmacists, (bio)informatics specialists, and biologists collaborating on nanoscience in biology and medicine. The interaction among these groups should accelerate discovery in nanoscience. It currently involves approximately 60 faculty, in a 'no-walls' model using facilities in the Engineering, Medical and LSA schools.

The long-term goals of the Institute are to advance science and commercialize discoveries, to enhance competitiveness for externally funded grants and contracts, to establish a Rackham Certificate program in Nanotechnology, and to design and offer an undergraduate overview Nanotechnology course taught by multiple faculty.

Solid State Electronics Laboratory (SSEL)

The SSEL manages academic programs and conducts research on the theory, design, and fabrication of electronic, optoelectronic devices, circuits, and microsystems (MEMS), as well as on organic devices, novel characterization and metrology techniques, and nanofabrication technology.

SSEL offers one of the most comprehensive and innovative education programs in the country dealing with all aspects of solid-state devices, circuits, and technologies. SSEL is home to two nano-related academic majors offered by the EECS department (Solid State and Microsystems and MEMS).

UNIVERSITY OF ILLINOIS-CHICAGO

Nano related Facilities

Micro/Nano Systems Committee (MNS)

The purpose of the Micro/Nano Systems Committee is to promote research and dissemination of knowledge in theoretical and applied research in micro- and nano-scale systems including, but not limited to, micromechanisms, micro- and nano-robotics, dynamics and vibrations of micro/nano-scale systems (MEMS/NEMS), microfluidics, BioMEMS/NEMS, and bio-systems design, sensors and actuators.

PURDUE UNIVERSITY

Nano related Facilities

Assessment of Nanomaterials in the Environment

Purdue University scientists are investigating the interactions between these tiny, many-sided structures and the environment. To further this research, the National Science Foundation (NSF) and Environmental Protection Agency (EPA) have awarded grants totaling nearly \$2 million to the Purdue Nanoscale Interdisciplinary Research Team and a colleague from the University of Minnesota. (For information on sponsored courses, go to <http://www.ydae.purdue.edu/ANE/courses.htm>).

Appendix E. Course Information for Nanotechnology; Programs and Concentrations

Curriculum for the A.A.S. Degree in Nanoscience Technology from Dakota Technical College

Course number, course name, credits

NANO1100 Fundamentals of Nanoscience I, 3
NANO1200 Fundamentals of Nanoscience II, 3
NANO1210 Computer Simulation, 1
NANO2101 Nanoelectronics, 3
NANO2111 Nanobiotechnology/Agriculture, 3
NANO2121 Nanomaterials, 3
NANO2131 Manufacturing Quality Assurance, 2
NANO2140 Interdisciplinary Lab, 3
NANO2151 Career Planning and Industry Tours, 1
NANO2970 Industry Internship & Observation, 2
Total Credits, 24

Capstone at the University of Minnesota

MT 3111 Elements of Microelectronic Manufacturing, 3
MT 3112 Elements of Micro & Nano Manufacturing. Laboratory, 1
MT 3121 Thin Films Deposition, 3
MT 3131 Introduction to Materials Characterization, 3
MT 3132 Materials Characterization Laboratory, 1
MT 3141 Principles & Applications of Bionanotechnology, 3
MT 3142 Nanoparticles and Biotechnology Laboratory, 1

Total Credits, 72

General Education

BIOL1500 General Biology, 4
COML1400 Introduction to Computers, 3
ENGL1100 Writing and Research Skills, 3
CHEM1500 Introduction to Chemistry, 4
MATS1250 Principles of Statistical Analysis, 4
MATS1300 College Algebra, 4
PHYS1100 College Physics I, 4
PHYS1200 College Physics II, 4
SPEE1020 Interpersonal Communication, 3

Total Credits, 33

TOTAL Program Requirements, 72 Credits

Northwestern University

MEMS/Nanotechnology Concentration in Mechanical Engineering

5 courses total

ME 381 Introduction to MEMS
ME 382 Experiments in Micro/Nano Science and Engineering
ME 385 Nanotechnology

Two courses from the list below and only one for each subgroup:

Materials and Characterization:

ME 317 Molecular Modeling and the Interface to Micromechanics
ME 319 Applications of Surface Science to Nanomechanics and Nanotribology
ChE 361 Introduction to Polymers
MSc 395 Special Topics: Biomaterials
MSc 395 Special Topics: Colloids

MSc 395 Special Topics: Nano-materials
MSc 360 Introduction to Electron Microscopy
MSc 380 Introduction to Surface Science and Spectroscopy
Devices and Control
ME 389 Molecular Machines in Biology
ME 391 Fundamentals of Control Systems or EECS 360 Introduction to Feedback Systems
EECS 388 Microelectronic Technology
BME 317 Biochemical Sensors
BME 321 Theory and Control of Biological Systems
BME 343 Biomaterials and Medical Devices

Nanomaterials Concentration in Materials Science and Engineering

5 courses

MSc 355 Electronic Materials
MSc 360 Introduction to Electron Microscopy
MSc 376 Nanomaterials
ME 381 Introduction to MEMS
ME 385 Nanotechnology

Surface Science Concentration in Materials Science and Engineering

5 courses

MSc 322 Kinetics of Heterogeneous Reactions
MSc 355 Electronic Materials
MSc 362 Point, Line and Planar Imperfections
MSc 380 Introduction to Surface Science and Spectroscopy
Phys 335 Modern Physics for Nonmajors