

Nanotechnology—A Frontier for Engineering Education*

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The preparation of a nanotechnology workforce for the next decade is a major challenge for the progress of this new technology. It is estimated that about 2 million workers will be needed worldwide in 10–15 years from now. Most of the major disciplines converge at the nanoscale toward the same building blocks, principles and tools of investigation. This paper outlines key US education and training activities in the general context of the National Nanotechnology Initiative that was announced in January 2000. Investigation of systems at the nanoscale requires an increase role of engineering education. Specific education models and the institutionalization of nanotechnology curricula in grades K to 12 and academic institutions are recommended for achieving a modern education system.

NANOTECHNOLOGY AND ITS EDUCATIONAL NEEDS

THE ESSENCE OF NANOTECHNOLOGY is the ability to work at the atomic, molecular and supramolecular levels, in the length scale of about 1 to 100 nm range, in order to create, manipulate and use materials, devices and systems with fundamentally new properties and functions because of their small structures. It includes understanding of phenomena and processes at the nanoscale, and integration of nanostructures along larger scales.

All materials and systems establish their foundation at the nanoscale. A water molecule is about 1 nm in size, a single wall nanotube is about 1.2 nm in diameter, the diameter of the man-made arm of a T4 phage (see Fig. 1) is about 3 nm, a typical pyramid quantum dot of germanium on a silicon substrate is about 10 nm wide, and the smallest transistors are few nanometers in laboratory and about 15 nm in prototypes. DNA molecules are about 2.5 nm wide, a typical protein is between 1 and 20 nm, and an ATP biochemical motor encountered in living cells is about 10 nm in diameter. A molecular machine may be dwarfed by the size of a human cell. Size confinement effects, quantum phenomena and Coulomb blockage are relevant under 30 nm feature size. Large surface area and high reactivity are dominant in the same region.

These are only a few examples from an unimaginable variety of material structures and properties! Control of matter at the nanoscale means tailoring the fundamental structures, properties, processes and functions exactly at the scale where the basic properties are defined. Some structure and properties may be generated beyond what

we have found in nature. This is the ultimate manufacturing length scale, as we know nature now. Rearranging the matter using ‘weak’ interactions such as H-bonds, van der Waals forces, electrostatic dipoles, fluidics, and various surface forces, would require low-energy consumption for manufacturing at this size of scale.

Nanotechnology includes integration of such nanoscale structures into larger material component, systems and architectures that could be used in most industries, healthcare systems and environments. The 1 nm molecular device size may be compared with the 100 nm critical feature size in current silicon chip technology, which could translate into a 10,000 times increase in the number of devices per chip. The combination of nanoscale assembly by DNA scaffolding with such compatible device and circuit architectures might some day lead to machines for processing information that are radically different from those of today and are manufactured by methods and operate on principles inspired by biological systems. Since all objects establish their foundation at the nanoscale, and their properties could be tailored at that scale for a given purpose, nanotechnology could revolutionize the production of almost all human-made objects.

Living systems work at the nanoscale and are governed by molecular processes that have been optimized along millions of years. Research is now seeking systematic approaches to engineer human-made objects at nanoscale and integrate nanoscale structures into larger-scale structures as nature does. While the specific approach may be different from the slowly evolving living systems in aqueous medium, many concepts such as self-assembling, templating, and integration at multiple length scales can be used as models.

Most of the current research activities are directed towards nanoscience. Only relatively

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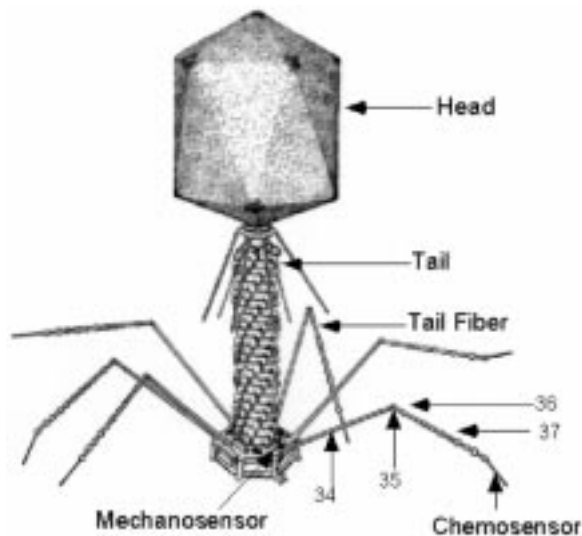


Figure 1. Illustration of a nanosystem: the T4 phage with its protein rod-like tail fibers (after Goldberg, NSF Conference [1]). The rods have 3-nanometer diameters and are subject to engineering manipulation. The research goal is to create three-dimensional patterns with artificially created protein rods.

simple nanostructures can economically be manufactured at the industrial scale, such as nanolayers, dispersions and nanoparticles and two-dimensional lattices. The level of complexity of industrially produced nanostructures and societal implications of nanotechnology are expected to increase rapidly in the next decade. Demands are being made on industry to attract new ideas, protect intellectual property, and develop nanotechnology-based products. Nanotechnology encompasses multidisciplinary aspects in biology, physics, chemistry, engineering, materials science and other disciplines. The field will require significant scientific advances toward unifying concepts for the large variety of laws and constants currently used in nanoscale analysis. A broad strategy is necessary to educate school children, technicians, and support students and postdoctoral fellows under fellowships that will attract some of the best students available.

Scientific discoveries and technological innovations are at the core of human endeavor. Besides the societal needs of wealth, health and peace, there is an intrinsic need for intellectual advancement, working at the frontiers. The intellectual drive toward nanoworld has been the initial underlying reason for the current focus on nanotechnology. Most of the major disciplines, from physics and chemistry to engineering, converge at the nanoscale toward same basic structures, principles and tools of investigation. Nanoscience provides a common meeting place and stimulates more fundamental research and education. In the last centuries, mechanical devices allowed us to reach beyond our physical strength and advance into technical civilization. Nanoscience and nanoscale manufacturing will allow us to reach beyond our natural size limitation and work directly at the building blocks of matter where all properties of

matter are defined and can be changed. This will spawn a new kind of industrial revolution in coming decades. Nanotechnology holds the promise of scientific breakthroughs in a wide range of fields, has an immense potential for industry and overall economy, for better health-care and sustainable environments.

The broader perspective of qualitative changes

Nanotechnology will bring changes in society that cannot be underestimated; some changes are unpredictable, some may imply risks besides the desired benefits. There is an explosion of discoveries in the last few years, and this is expected to accelerate in the next decade. Many scientific advancements exceed the projections made just one year ago, in areas such as molecular electronics, guided self-assembling, medicines and DNA processing, to name a few. Arranging the atoms and molecules in tens to hundreds of thousands of atom structures to get special properties could be possible with low consumption of material and energy—only one needs to learn the way to efficiently obtain a property or function ‘by design’. Systematic development of new material properties, system functions and multiscale products from basic principles at the nanoscale is expected to become the main endeavor in manufacturing industries. There are transcendent trends in working at the nanoscale, from the confluence of science and technology to the ability to change living systems at the subcellular level.

Academic and private sector communities alike are developing a robust belief about the potential scientific and technological outcomes in the longer term. The nanotechnology expectations are broader than for other major endeavors in the past, such as the Manhattan nuclear project and landing on the moon. Nanoscale science and engineering promises restructuring of almost all industries towards a new foundation, reshaping our intellectual comprehension of nature, and assuring the quality of life in an increasingly crowded planet with shrinking energy and materials resources and less environmental endurance. The blossom of two flagship technologies, information and bio, would be severely threaten without the concepts, tools, materials, systems and synergism provided by future nanotechnology growth.

Educational programs need to be refocused from microanalysis to nanoscale understanding and creative manipulation of matter at the nanoscale. A unified coherent education system using understanding from the basic components of nature is envisioned. Bio-medical sensors and nanodevices may enhance the performance of human body and prolong its life, and the role of innovation in nano-engineering new products in an interconnected world could become the key factor in the progress of humanity. Specific ethical and legal aspects will need to be considered at the beginning of research and development (R&D)

projects because the nanoscale is touching the foundation of biosystems.

The need of nanoscientists and nanotechnologists

A key challenge for nanotechnology development is the education and training of a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress of the new technology. Opportunities should be created for most K-12 students (about 50 million in U.S., 2001). The concepts at the nanoscale (atomic, molecular and supra-molecular levels) should penetrate the education system in the next decade in a similar manner to how the microscopic approach made inroads in the last forty to fifty years. Such education and training must be introduced at all levels, from kindergarten to continuing education, from scientists to non-technical audiences that may decide the use of technology and its funding. It is estimated that about 2 million nanotechnology workers will be needed worldwide in 10–15 years [2]. If one would extrapolate the current proportion of the users of key measuring instrumentation (atomic force microscopes and scanning tunneling microscopes), it would obtain a rough distribution of nanotechnology workers needed in various areas in 2010–2015 [3]:

- 0.8–0.9 million in US;
- 0.5–0.6 million in Japan;
- 0.3–0.4 million in Europe;
- 0.1–0.2 million in Asia-Pacific region excluding Japan;
- million in other regions.

Because developments are not linear, such estimation may change in the future. One way to ensure the pipeline of new students in the field is to promote the interaction with the school system and the public at large. Several US universities have reported increased numbers of highly qualified students moving into physical and engineering sciences in the last year because of research supported by the National Nanotechnology

Initiative (NNI). University outreach activities should also stimulate innovation in industry and international interactions.

FROM U.S. NATIONAL NANOTECHNOLOGY INITIATIVE TO INTERNATIONAL R&D FOCUS

The National Nanotechnology Initiative (NNI) [4–7] is characterized by:

- high-risk–high-return;
- interdisciplinary nature of R&D;
- broad societal implications.

President Clinton introduced NNI to the Nation during a speech at the California Institute of Technology in January 2000. The US Congress approved the NNI budget of \$422 million in fiscal year 2001 (October 2000 to September 2001), a 56% increase over the previous year. The letter sent in summer 2000 by the Office of Science and Technology Policy and the Office of Management and Budget to all agencies has placed nanotechnology at the top of the national R&D priorities for the fiscal year 2001. The increase of nanotechnology investment in fiscal year 2002 is by \$182 million or about 43%. The investments made in ten US departments and independent agencies are shown Table 1.

NSF has the largest investment of \$150 million in fiscal year 2001 and of \$199 million in fiscal year 2002 on programs embracing topics from chemistry, materials, molecular biology and engineering to revolutionary computing, mathematics, geosciences and social sciences. The first ‘nano’ program on Nanoparticle Synthesis and Processing at high rate production has began in 1991. In fiscal year 2001, the budget allocated to NNI counted for about 0.5% of the US Federal R&D investment. The US funding contribution to the world R&D effort was about 30%.

International activities develop in a ‘self-assembled’ mosaic, which has several characteristics [3]. The R&D focus is different from one

Table 1. Summary of U.S. Federal nanotechnology investment in fiscal years 2000 to 2002 (in \$ millions)

Department/Agency	FY 2000 NNI Budget	FY 2001 NNI Budget	FY 2002 Budget Request
Department of Defense (DOD)	70	110	140.0
Department of Energy (DOE)	58	93	96.0
Department of Justice (DOJ)	—	—	1.4
Department of Transportation (DOT)	—	—	2.0
Environmental Protection Agency (EPA)	—	—	5.0
National Aeronautics and Space Admin. (NASA)	5	20	46.0
National Institutes of Health (NIH)	32	39	45.0
National Institute of Standards and Techn. (NIST)	8	10	17.5
National Science Foundation (NSF)	97	150	199.0
U.S. Department of Agriculture (USDA)	—	—	1.5
Total***	270	422	604.2 (+43%)

Notes: Figures are not available for six departments that participate in the federal nanotechnology investment starting with January 2001: Department of Commerce (DOC), Department of State (DOS), Department of Treasury (DOTreas), and Nuclear Regulatory Commission (NRC).

Table 2. Estimated government nanotechnology R&D expenditures (in \$ millions/year; survey August 2001)

Area	2000	2001	(2002)
W. Europe	200	225	
Japan	245	410 + 140*	
USA	270	422	543
Others	110	380	
Total	825	1577	
(% of 2000)	(100%)	(191%)	

Note: 'W. Europe' includes countries in EU and Switzerland; 'Others' include Australia, Canada, China, FSU, Korea, Singapore, Taiwan, Eastern Europe and Middle East countries with nanotechnology R&D programs; this estimations use the nanotechnology definition as in NNI [4]. * Appropriated by Congress a financial year begins in USA on October 1 of the previous calendaristic year, and on March 1 or April 1 of the respective calendaristic year in most other countries.

country to another. An increasing interest is on various aspects of nanoscale manufacturing. Education and training is becoming a key component of the long-term national objectives. There are common scientific and technical challenges addressing broad humanity goals such as sustainability and improving human performance. Partnerships are increasingly seen as necessary for rapid advancement and international recognition, as well as a requirement for interdisciplinarity and

integrative R&D activities. International collaboration in nanotechnology has accelerated since 2000.

Table 2 shows the estimations for the government nanotechnology R&D budgets for the main contributing areas. The investments have almost doubled in 2001 as compared to the previous year. This is an unprecedented worldwide rate of increase for a comprehensive R&D field.

NANOSCALE SCIENCE AND ENGINEERING EDUCATIONAL ACTIVITIES IN THE U.S.

Interdisciplinary focus on nanoscale science and engineering education has begun only in the last few years. Adding nanoscale perspective in teaching leads to better fundamental understanding, sharing similar concepts and courses in various disciplines and areas of relevance (combining the 'depth' of nanoscience with the 'breadth' of all affected areas), and broader accessibility to science and technology. The NNI education activities in 2001, and particularly those of the National Science Foundation (NSF), are illustrated in Table 3.

Curriculum development in universities.

A list of courses and course modules on nanoscale science and engineering offered at US

Table 3. Examples of courses on nanoscale science and engineering offered in US universities

Topic	University
Nano-course (for undergraduates, summer course)	Cornell Nanofabrication Facility (A. Clark, M. Isaacson)
'Capstone' course on nanotechnology ('hands-on' for softmore and two-year colleges)	Nanofabrication Facility, Pennsylvania State University (S.J. Fonash)
Semiconductor manufacturing and nanofabrication (laboratory for undergraduates)	University of California at Los Angeles (J.P. Chang)
Nanostructure science and engineering (for senior undergraduate and first year graduate students)	SUNY Buffalo, Amherst (D.T. Shaw)
Introduction to nanotechnology (for senior undergraduate and first year graduate students)	Southern Illinois University, Carbondale (E.J. Hippo)
Advanced quantum devices (for graduate students)	University of Notre Dame (EE 666)
Nanotechnology	Virginia Commonwealth University (M. El-Shall)
New technologies	University of Wisconsin, Madison (R. Hamers)
Nanostructured materials (for graduate students)	Rensselaer Polytechnic Institute (R. Siegel)
Colloid chemical approach to construction of nanoparticles and nanostructured materials	Clarkson University (J.N. Fendler)
Nanoparticles processes (for graduate students)	Yale University (D. Rosner)
Nanorobotics (for graduate students)	South California University (A. Requicha)
Chemistry and physics of nanomaterials	University of Washington (Y. Xia)
(a) Scanning probes and nanostructure characterization; (b) Nanoscale physics	Clemson University (D. Correll)
Nanomanufacturing processes, using Distributed Interactive Studio House (DISH), a multimedia classroom integrated laboratory	University of Arkansas, in partnership with states Arkansas, Oklahoma and Nebraska (A.P. Malshe)
Nanoscale science and engineering	Purdue University (R. Reinfenberger)
Mathematics in Nanoscale science and engineering (for graduate and postgraduate students)	University of California at Los Angeles (M. L. Green)

universities in 2001 is shown in Table 3. The main needs are for interdisciplinary overview courses for the undergraduate freshman/softmore years and graduate first year, and the inclusion of nanoscale science and engineering course components in the existing curricula.

Integration of research and education.

The goal is to make every laboratory a place of learning. About 5,000 students, technicians, teachers and faculty were prepared in 2001 with NSF support. Each group and center award generally includes an education and outreach component.

An example is the Integrative Graduate Education, Research and Training (IGERT) program funded by NSF since 1999, where graduate students receive fellowships for interdisciplinary topics and move under the guidance of several professors with various expertise. The list of related IGERT projects is given in Table 4. The awards are made for five years.

An IGERT illustration is the 'Nanophases in the Environment, Agriculture and Technology' grant at the University of California, Davis [8]. The grant funds a multidisciplinary research and education program which links the fundamental physics, chemistry, and engineering of small particles and nanomaterials to several challenging areas of investigation:

- Applications in ceramic, chemical, electronic, environmental, and agricultural technology.
- Environmental transport and transformation, and resulting roles in environmental pollution and remediation.
- Interactions with the biosphere, especially microorganisms.
- Effects on health.

The program involves 14 faculty in eight departments in four colleges: the College of Engineering, the College of Letters and Science, the College of Agricultural and Environmental Sciences, and the College of Veterinary Medicine, and offers funds for the support of 14 Ph.D. students per year.

Students in four-year doctoral programs will generally receive about half their funding from the IGERT. Over the course of its five years, NEAT will have 50–60 graduate students and 10–20 undergraduate student participants. By bringing together faculty and students in fields ranging from the nanoelectronics to the interaction of nanoparticles in soils, water, and air with living organisms, this program will both educate students broadly and provide a basis for exploring common features of nanoscale materials originating in many different ways.

- Department of Defense (DOD) fellowships in nanoscience in 2001. These are individual awards for Ph.D. students to follow interdisciplinary nanoscience projects [9].
- National Nanofabrication User Network (NNUN), with the lead institution at the Cornell University, offers undergraduate and graduate courses; the NNUN experimental facilities and projects are used as illustrations in teaching [10].
- Combined Research Curriculum Development (CRCD) program offers a special opportunity for integration of research and education in the field of nanotechnology (Table 5) [11]. The awards are for three years with the expectation that the educational programs will continue after that interval.
- Research Experience for Undergraduate (REU) and Research Experience for Teachers (RET) sites funded by NSF. Examples are the REU sites for nanotechnology at Cornell University and nanomaterials processing at the University of Central Florida, and the RET on nanoscale copolymer at University of Massachusetts, Amherst.

Local and long-distance outreach education

A group of academic institutions have begun to provide local and long-distance outreach activities via internet and television in the field of nanoscale science and technology, including laboratory experience. Outreach activities are focused on K–12 (Kindergarten through 12th grade),

Table 4. Examples of IGERT projects with focus on nanoscale science and engineering

Topic	University (lead investigator)	Starting year
Nanophases in the Environment, Agriculture and Technology (NEAT)	University of California -Davis (A. Navrotski)	1999
Nanostructured Materials and Devices	City University of New York (D.L. Akins)	2000
Nanobiotechnology	University of Washington (A. Vogel)	2000
New materials for electronics and optics through control of nanoscale structure	University of Oregon (D. Johnson)	2001
Nanoparticle science and engineering	U. of Minnesota (U. Kortshagen)	2001
Multidisciplinary graduate materials creation training program	University of California, Los Angeles (F. Wudl)	2001
Macromolecular science and infrastructure engineering	Virginia Polytechnic Institute and SU (J. Riffle)	2001
Biophotonics materials and applications	SUNY-Buffalo (A. Cartwright)	2001

Table 5. Examples of CRCD projects focused on nanoscale science and engineering

Topic	University (lead investigator)	Starting year
Computer simulation of materials from atomistic to the continuum level	Virginia Polytechnic Institute and State University (R. Krill)	1997
World wide web-based textbook on molecular simulation	University of Tennessee—Knoxville (P. Cummings)	1997
Computational materials science and nanoscale science and engineering	University of Illinois at Urban (DM Ceperley)	2001

academic institutions without strong infrastructure, and public at large. Several illustrations are:

- University of Wisconsin, education for schools and public at large [12, 13].
- University of North Carolina, ‘The nanoManipulator’ [14].
- Rensselaer Polytechnic Institute, long distance undergraduate laboratory experience in nanoscience.
- Rice University, ‘Introduction to Nanoscience’ [15] website.
- University of Tennessee, ‘Molecular Modeling and Simulation’ network on the Internet.
- Arizona State University, ‘Interactive Nano-Visualization in Science and Engineering Education’ [16].
- University of Illinois at Chicago, course on ‘Micro and nano-electronic processes’.
- Other activities as part of the research centers and networks (see under Education and training below).

For example, the objective of the University of Wisconsin website [12] is to introduce viewers to the tools that let us ‘see’ atoms, manipulate them, and create nano-architectural wonders. Viewers can investigate the frontiers of the nanoworld by learning how materials are customized to create everything from atomic trampolines to DNA to ferrofluids to semiconductors that emit blue light. This site is a resource for education and outreach efforts associated with the National Science Foundation-supported Materials Research Science and Engineering Center on Nanostructured Materials and Interfaces based at the University of Wisconsin-Madison (MRSEC, contact Prof. A. Ellis, ellis@chem.wisc.edu). Elementary school material is available on the Internet [13, b].

Technological education

This is a major challenge that has been addressed in only a few projects. Two leading projects are:

- The Pennsylvania State University (S. Fonash) has created the Regional Center for Nanofabrication Manufacturing Education with the state and NSF grant support for 2001–2004. A partnership between the state, 14 universities, all state community colleges, vocational technical school, and industry has been established to enhance the state of Pennsylvania workforce preparation in nanotechnology. It targets

degrees and outreach in Nanofabrication Manufacturing Technology via new curricula at community colleges and universities, training the teachers and community college educators, promoting awareness of career opportunities [17].

- The Nanotechnology Research and Teaching Facility, College of Engineering in University of Texas at Arlington, has been established in 2001. This facility will provide laboratory hands-on training for technical, undergraduate and graduate education.

Education and training in centers and networks

Large research groups, centers and networks offer interdisciplinary/multi-relevance opportunities for both R&D and education and training. NSF has established six Nanoscale Science and Engineering Centers (NSEC) in September 2001 under the NNI. Those centers are funded for five years, and are renewable after review in 2006 for other five years. Their educational and outreach activities in addition to diversifying graduate education are summarized in Table 6. This is an extension of the tradition of significant education and outreach activities at the National Nanotechnology User Network (NNUN), ‘Dechartes’ nanoscale simulation network [1], and Science and Technology Center on Nanobiotechnology at Cornell University, as well as at several Materials Research and Engineering Centers (MRSEC) and Engineering Research Centers (ERC).

For example, the NSEC education activities at Cornell University will include the K–12 Teacher Institute, freshman Introduction to Nanotechnology course, Nanotechnology Equipment Lending Library with nanoscience experiments for use by teachers with high-school students, Montessori K–4 curriculum development, and a modular traveling exhibition for the family Ithaca Science Center.

Modules for individual training

This is a relatively new trend that has originated from the need of individual specialization and training using relatively sophisticated methods and equipment. Examples are:

- The University of Massachusetts (Mark Tuominen’s group) and Boston University (Gene Stanley’s group) developed short modules for individual training in various aspects of nanotechnology.
- Modules on the ‘Interactive Nano-visualization

Table 6. Nanoscale Science and Engineering Centers (NSEC) funded in September 2001.

NSEC (2001–2006)	University (Lead investigator)	Key educational activities (in addition to graduate education)
Electronic Transport in Molecular Nanostructures	Columbia University (J. Yardley)	Engaging high school students in collaboration with the City University of New York; and mentor undergraduates and graduates through specialized summer and academic year programs.
Nanoscale Systems in Information Technologies	Cornell University (Robert Buhrman)	Partnering with industry to support a K–12 Teachers Institute and a nanotechnology teaching laboratory; freshman Introduction to Nanotechnology; collaboration with Ithaca Sciencecenter (travelling exhibition)
Science of Nanoscale Systems and their Device Applications	Harvard University (Robert Westervelt)	Outreach to middle school students and teachers; and fostering public education in partnership with the Boston Museum of Science.
Integrated Nanopatterning and Detection Technologies	Northwestern University (Chad Mirkin)	Web-based outreach to high school science teachers and the development of curriculum material for middle and high schools; Initiating a small business entrepreneurs program; Partnering with the Museum of Science and Industry in Chicago; summer research programs for minority undergraduates.
Directed Assembly of Nanostructures	Rensselaer Polytechnic Institute (Richard Siegel)	Partnerships with industry and several colleges (Morehouse, Mount Holyoke, Smith, Spelman and Williams) to enhance research opportunities for groups that are underrepresented in science; K–12 teaching program in collaboration with the Junior Museum of Troy.
Nanoscience in Biological and Environmental Engineering	Rice University (Richard Smalley)	Identify, recruit, and train a nanoscience workforce, particularly among groups currently underrepresented in the science workforce; a partnership with the Jones Graduate School of Management for an entrepreneurial education program.

in Science and Engineering Education' website at the Arizona State University [16].

- Internships for industry researchers may be offered for completing graduate studies. This may be done with NSF support (Grants for Academic Liaison with Industry [18]) or through industrial sponsors (ex: Merck at the Rutgers University in the area of nanoparticles)

Public education (non-technical audiences)

The public is the ultimate user and sponsor of the new technology. The importance of this activity has been underlined in a recent study on societal implications of nanoscience and nanotechnology [2]. Illustrations are already listed in Table 6, for example the NSEC at Harvard University has outreach activities with the Boston Museum of Science. Also, NSF has sponsored projects focused specifically on public science education. Examples are:

- The University of Wisconsin and Discovery World science museum in Milwaukee for 'making nanoworld comprehensible'.
- The Arizona Science Center for internship for undergraduate students and schoolteachers for programs with emphasis on nanotechnology for public and school outreach (three-year grant for Internships for Creating Presentations on Nanotechnology Topics at a Science Center).
- In a broader context, NSF organized an outreach activity, Small Wonders: Exploring the Vast Potential of Nanoscience, for the public and non-specialists (at the Washington, DC, World Trade Center; see the NNI website [4]).

Courses and tutorials offered by professional societies

These activities offer a unique opportunity for dissemination of the field and continuing education. Most effective courses cover basic concepts for various disciplines and broad areas of relevance, and show where is the role of the respective community and professional group in advancing nanotechnology. A second group of relatively fewer courses is addressed to industry and are focused on shorter-term nanotechnology outcomes. A third group of courses addressed to academic participants and retraining is on specialized topics, such as nanotechnology tools and manufacturing methods. Examples are the tutorials offered by American Chemical Society, American Vacuum Society, and American Society of Mechanical Engineering, as well as the educational websites established by Materials Research Society (MRS) [19] and Institute of Electrical Engineering and Electronics [20].

International dimension

International interactions increase on an accelerating path. Exchange of information, leveraging the research efforts, and education of younger generations are the main reasons. About one third of projects in the small-group research activities under the NSF program Functional Nanostructures have international collaborations. NSF has sponsored young researchers for group travel to Japan, EU and other areas to present their work and visit centers of excellence in the field. Bilateral and international activities have been under way since 2000 with European Union, Japan, Korea, India, Switzerland, Germany, Latin America,

APEC, to name the most important. For example, NSF and EC organize four joint workshops in 2002 in manufacturing, societal implications and education, tools, and materials. All those workshops have an education component, and younger nanoscale science and engineering researchers are invited. Exchange of information should be expanded in curriculum development and long distance learning. Programs in China and Korea were highlighted by the International Conference on Engineering Education [21] in 2001 in Norway.

A FRONTIER FOR ENGINEERING

The role of engineering

Physical, chemical, biological and engineering sciences have arrived at the nanoscale about the same time. R&D for nanotechnology are at the confluence of many disciplines and areas of relevance, including engineering. Engineering will play an important role because when we refer to nanotechnology we speak about ‘systems’ at the nanoscale, where the treatment of simultaneous phenomena in multibody assemblies would require integration of disciplinary methods of investigation and an engineering problem-driven approach. The manipulation of a large system of molecules is equally challenging to a thermodynamics engineer researcher as it is to a single-electron physics researcher. They need to work together at the intermediate length scale.

The special role of an engineer in nanotechnology may be underlined by several reasons:

- Nanotechnology deals with relatively large systems at the nanoscale, typically with components in the range of hundreds or thousands, where the interacting components or simultaneous phenomena cannot be treated independently. For instance, in an array of quantum dots, besides the interaction among the dots, their interaction with the neighboring surfaces and wiring need to be considered.
- Nanotechnology requires the integration of methods of investigation from various disciplines, in order to understand macroscopic phenomena, define transport coefficients, and optimize processes and design products. Various methods need to be considered at different length scales. For instance, multiscale modeling of dynamic fracture would require finite element simulation of continuum elasticity, then atomistic simulation of Newton’s equation and thereafter electronic simulation of Schrodinger’s equation.
- Nanotechnology implies the ability to manipulate the matter at nanoscale under control, and integrate along scales to manufacture material structures, devices and systems. Main challenges are creation of tailored structures in the submicron to the 100 nm range, combination of the bottom-up and top-down approaches to

generate nanostructured devices and systems, interaction of living and non-living structures, replication and eventually self-replication methods at nanoscale, and development of new concepts that would allow for large-scale production and economic scale-up.

- Development of tools and processes to measure, calibrate, design and manufacture of nanostructures requires engineering methods.

ACTIVITIES ENVISIONED FOR ENGINEERING EDUCATION

The engineering community may consider several lines of actions:

- *Improving education and training of engineers* to better understand phenomena and processes from the atomic, molecular and macromolecular levels. This may include introducing new course modular sections in existing engineering courses, teaching overview nanotechnology courses on nanotechnology at the freshman undergraduate year and first year graduate school, continuing education and retraining programs.
- *Addressing problem-driven, interdisciplinary R&D* through inter-departmental collaborations. Close collaborations between chemical, electrical, mechanical and bio-engineering should be encouraged within the engineering profession, in addition to physics, chemistry, biology, and material sciences.
- *Redefining the current role of engineering* from the analysis and design mainly at the macro- and microscales towards nanoscale engineering. Modern biology, electronics, and other areas have already moved their research and education areas of focus at the nanoscale. One can foresee significant rewards and challenges. Engineering has a wide net, from molecular thermodynamics, nanoparticles, nanostructured materials and nano-electro-mechanical systems (NEMS), electronic and photonic devices to nanoscale interpretation of transport phenomena and solid mechanics.
- *Identifying research and education grand challenges in nanotechnology*, such as those related to energy conversion, nanomechanics, and nanoelectronics, where engineering could play an important role.
- Using opportunities of partnering with the emerging nanotechnology ‘regional alliances’.

The following specific needs have been identified for education and training:

- Encourage a system approach in teaching nanoscale science and engineering at all levels.
- Underline interdisciplinarity, sharing the same basic concepts from one field to another, and creating the environment for nanoscale R&D advancements in all relevant disciplines from

electronics, biology and materials to engineering system integration.

- Underline an unified scientific treatment in theory and simulation, including topics on manufacturing processes and system architecture at the nanoscale.
- Provide increased attention to continuing education and technical education.
- Active outreach from universities and other research centers is essential for achieving the desired societal implications; The outreach is addressed to K–12, undergraduate and continuing education, as well as to industry innovation, general public and international aspects.
- A challenge is communication and generalization of the positive results, their integration into the general curriculum, and institutionalization of nanoscale science and engineering in K–12 and university education. Engineering should play a key role in this process because of its system, integrative and interdisciplinary approach of investigation. School boards and school superintendents should be involved from the beginning in planning such activities.
- Increasing the international dimension of both nanotechnology R&D and industrial production would require suitable internationally-oriented training for the US students.

While establishing the nanotechnology workforce may benefit from similarities with information technology [22] and biotechnology [23], the time interval available for development appears to be shorter and implications are at least as broad.

CONCLUDING REMARKS

It is expected that the foundation in engineering education will move from the microscopic to the molecular and supra-molecular levels in the next 10–15 years. Nanoscale science and engineering provides a common meeting place for disciplines towards the same basic material structures, principles and tools of investigation, and stimulates more fundamental research and education. Systemic changes by extending the models discussed in previous sections are envisioned in teaching the nanoscale concepts, from kindergarten

to graduate schools and continuing education for retraining. Efforts should be made to institutionalize nanotechnology education in K–12 and higher education academic institutions, and to encourage introduction of the new concepts in all relevant disciplinary courses including physics, chemistry, biology, materials and engineering. An important corollary activity is the retraining of teachers themselves. Interdisciplinary fellowships are to be emphasized in graduate research.

Nanotechnology will require that a new world of knowledge be covered. Unifying science and converging technologies on this basis should be reflected in education. Engineering should play an important role because when we refer to nanotechnology we speak about ‘systems’ at the nanoscale, where the treatment of simultaneous phenomena in multibody assemblies would require integration of disciplinary methods of investigation and an engineering system approach. Engineering community needs to extend its role of analysis, design and manufacturing at the macro- and microscales to include nanoscale engineering.

It is estimated that nanotechnology will enter our lives in a significant manner in 10–15 years. The availability of sufficient scientists and industrial experts is uncertain if we continue on the current path. One may consider changes in way we structure the information on nanotechnology in order to improve learning and disseminate the results. Engineering and particularly manufacturing at the nanoscale will increase in importance. A five-year goal of the NNI in the US is to ensure that 50% of research institutions’ faculty and students have access to a full range of nanoscale research facilities and student access to education in nanoscale science and engineering is enabled in at least 25% of the research universities.

Nanoscale science and know-how is growing throughout the world and international interaction is a key for bringing alive faster the benefits of nanotechnology.

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