Converging science and technology at the nanoscale: opportunities for education and training

Mihail C Roco

Reversing the pyramid of learning could expedite the development of a US nanotechnology workforce.

Nanoscale science and engineering are providing us with unprecedented understanding and control of matter at the most fundamental level: the atomic and molecular structures that are the foundation of all living systems and man-made products. Indeed, the same principles and phenomena apply at the nanoscale across every discipline, leading to increased coherence in knowledge, education and technology. The key goals of nanotechnology are advances in molecular medicine, increased working productivity, extension of the limits of sustainable development and increased human potential. And yet, one of the 'grand challenges' for nanotechnology is education, which is looming as a bottleneck for the development of the field, and particularly for its implementation. In 10 to 15 years, we may have the research results from the new technology without having the workers to take advantage of them. This article will discuss how to better prepare human resources for the development of nanotechnology.

The United States has initiated a multidisciplinary strategy for the development of science and engineering fundamentals through the National Nanotechnology Initiative (NNI)[1]. The Federal budget for fiscal year 2003 is $770 million, and the request for FY 2004 is $849 million. The NNI's annual investment in cross-disciplinary research with educational and societal implications is estimated at about $30 million in FY 2002, of which the national Science Foundation (NSF) awards about $23 million, including contributions to student fellowships.

Mihail C. Roco is at the National Science Foundation, 4201 Wilson Boulevard, Arlington, Virginia 22230, USA.
e-mail: mroco@nsf.gov

Worldwide, nanotechnology research and development investment reported by government organizations has increased about sevenfold over the past six years, from roughly $430 million in 1997 to $3 billion in 2003. At least 35 countries have initiated national activities in this field, partially stimulated by the NNI vision.

Nanobiotechnology is defined as a field that applies nanoscale principles and techniques to understand and transform biosystems (living or nonliving), or uses biological principles and materials to create new devices and systems integrated from the nanoscale. Integration of nanotechnology with biotechnology, as well as with information technology and cognitive science, is expected to accelerate in the next decade. The basic processes of life—molecular subcellular mechanisms and formation of the tissues' primary structures—occur at the nanoscale. For this reason, understanding the design of biological systems can shape the development of highly efficient and versatile new devices and systems.

The investment in nanobiosystems research and education in the NNI is estimated to be about 15% of the FY 2002 budget, of which about 8% is for fundamental aspects, 4% for 'grand challenges' in the medical field and nanobiodevices and 3% in contributing infrastructure. Worldwide, excluding the US, the proportion of government-sponsored investment going into nanobiotechnology research and education is estimated to be about 6%. In the private sector, larger companies are currently focusing on applying nanotechnology to materials, chemicals and electronics; investment in pharmaceuticals and other nanobiosystems is estimated at roughly 10%. However, smaller companies and venture capital funds pay proportionally more attention to this topic (30–40%). Indeed, since nanobiotechnology is being recognized as the most promising of all nanotechnology fields for venture funds, smaller companies and venture funding may be a harbinger of nanotechnology's future.

If that is the case, then the implications for education and training are clear. First, careers will be needed for specific biomedical technologies, such as tools to regenerate bone or skin, to reverse paralysis, and to detect illnesses earlier, or for developing and delivering targeted drugs that safely treat cancer. Second, jobs will be created in nanobiomaterials and nanobioprocessing for manufacturing. Developing a better understanding of 'design in nature' may also pave the way for developing complex systems such as sensors for biological or chemical threats, rapid analysis of blood while at the doctor's office and magnetic separation of nanoparticle-labeled cells. What is necessary is deep knowledge in at least one field of nanotechnology, coupled with the ability to communicate and collaborate with other related nanotechnology areas as well as with experts in other fields. The younger personnel seems to be more inclined to address nanobiotechnology topics, whereas the decision in larger organizations remains dominated by people who have only tangential knowledge of this new field.

The need for 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. The concepts at the nanoscale (atomic, molecular and supramolecular levels) should penetrate the education system in the next decade in a manner similar to the way the microscopic approach made inroads in the last 50 years. Furthermore, interdisciplinary connections reflecting unity in nature need to be promoted. Such education and training must be introduced at all levels, from kindergarten to continuing education, from scientists to nontechnical audiences that may decide the use of technology and its funding. Opportunities should be created for most school students (about 50 million in the US alone in 2002). It is estimated that about 2 million nanotechnology workers will be needed worldwide by 2015 (ref. 2). If one extrapolates from the current proportion of the users of key measuring instrumentation (atomic force microscopes and scanning tunneling microscopes), an approximate distribution of nanotechnology workers needed in various areas in 2015 would be: 0.8–0.9 million in the US, 0.5–0.6 million in Japan, 0.3–0.4 million in Europe, 0.1–0.2 million in the Asia-Pacific region excluding Japan and 0.1 million in other regions. Extrapolating from previous experiences in information technology, where for each worker another 2.5 jobs are created in related areas, nanotechnology has the potential to create 5 million additional related jobs overall by 2015 in the global market[3]. On the supply side, for example, NSF has trained about 7,000 students and teachers in FY 2003. 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 interaction between the school system and the public at large. Several US universities have reported an increased number of highly qualified students moving into physical and engineering sciences in the last two years because of public recognition of nanotechnology and research supported by NNI. University outreach activities should also stimulate nanotechnology innovation in industry and international interactions.

The interest in each research topic can be estimated based on the trends in using typical nanotechnology instrumentation. Such estimates show that advanced materials have about 30% of all users, semiconductors and electronics about 25%, and nanobiotechnology (including pharmaceuticals, biology and medicine) about 20%, with the remaining 25% divided among tools, optics, electrochemistry, aeronautics and energy. Patent trends and new venture funding for 2002–2003 show an increase in the proportion of nanobiotechnology users to about 30%. Of 6,400 nanotechnology patents identified in 2002 at the US Patent and Trademark Office, the leading numbers are for molecular biology and microbiology (roughly 1,200 patents) and for drug, bio-affecting and body treating compositions (about 800 patents), together representing about 31% of the total patents in the respective year[4].

A new framework: reversing the pyramid

Today, undergraduate and graduate students are typically taught the various disciplines and methods of investigation first. Only in the final years of their PhD programs, at the top of the 'pyramid of learning,' do they begin to learn the connections. An alternative would be to provide freshmen and sophomores with unifying concepts for matter and biology systems at the beginning, and then advance to various disciplines that focus on phenomena and averaging methods for related length scales. In this way, one could move the same basic concepts from one field to another and create a synergistic view for potential applications in various areas of relevance.

The goal is a coherent and progressively comprehensive education. Knowledge would be connected and integrated, as it would be introduced from lower levels up. Reversing the pyramid of learning would provide a qualitative view and motivation to students in physical, chemical, biological and engineering sciences at all levels.

Challenges for developing a nanotechnology workforce

Since the physical infrastructure for nanotechnology education is still in formation, the main challenge is the interdisciplinary and timely formation of nanotechnology technicians, engineers, medics and scientists. Another challenge is bridging and synchronizing elementary, middle/high school, undergraduate, graduate and continuing education. Currently, we are benefiting from islands of creative and enthusiastic groups, such as those at Northwestern University, Cornell University and the University of California, Los Angeles.

A third challenge is to form a flexible workforce able to cross disciplines, areas of relevance and geographical lines. Increasing the international dimension of both nanotechnology R&D and industrial production would require suitable internationally oriented training for US students. International partnerships with the European Union, Japan, Taiwan, Korea and other countries have been developed or are under development.

Finally, communication and generalization of positive results, their integration into the general curriculum and institutionalization of nanoscale science and engineering in K–12 and university education is needed. Engineering should play a key role in this process because of its integrative and interdisciplinary approach. School boards and school superintendents should be involved from the beginning in planning such activities. A systemic change can only be made with sustained funding, long-range planning and proper communication with the public and executive and legislative branches of government.

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's educational activities in 2001, and particularly those of the NSF, are illustrated in Table 1.

New programs

The NSF has supported individual projects in nanoscale science and engineering as part of its core programs or as a component in larger research projects. In FY 2002, it announced the first of more than 30 awards toward nanotechnology undergraduate education. More recently, in August 2003, the NSF announced a new program, Nanoscale Science and Engineering Education (www.nsf.gov/nano), with four parts covering high school, informal education, undergraduate education and centers of education and learning. In the near future the NSF plans to extend the concepts of nanoscience to elementary schools.

Remote access to nanotechnology classrooms and laboratories is already available in various parts of the US. The establishment of two national networks, Network for Computational Nanotechnology (in 2002) and National Nanotechnology Infrastructure Network (in 2003), with extensive long-distance education and training capabilities, will allow broad access to nanotechnology education in the US.

Several institutions have begun offering degrees in nanotechnology, such as Penn State University (focused on nanostructured materials) and the University of Washington, Seattle (focused on nanobiotechnology). Offering joint degrees in a discipline and nanotechnology seems to be the most accepted path. Additional education and

Table 1 Typical nanotechnology education programs supported by the National Science Foundation

NSF program	Example
Curriculum development on nanoscale science and engineering offered in US universities	Undergraduate courses at the Nanobiocenter at Cornell University Graduate courses on nanoparticles, Clarkson University
Integration of research and education	Nanobiotechnology (Integrative Graduate Education and Research Traineeship), University of Washington, Seattle
Local and long-distance outreach education	'The nanoManipulator,' University of North Carolina 'Network for Computational Nanotechnology,' Purdue University 'Nanokids,' CD-based interactive video for high school, Rice University 'Molecularium,' imaging molecules from the inside, Rensselaer Polytechnic Institute
Technological and community college education	Regional center for nanofabrication manufacturing education, Pennsylvania State University
Education and training in centers and networks	Rensselaer Polytechnic Institute partnerships with industry and several colleges (Morehouse, Mount Holyoke, Smith, Spelman and Williams) to enhance research opportunities for groups that are under-represented in science; K–12 teaching program in collaboration with the Junior Museum of Troy
Modules for individual training	Modules on the 'Interactive Nano-visualization in Science and Engineering Education' website at Arizona State University
Public education (for nontechnical audiences)	University of Wisconsin and Discovery World science museum in Milwaukee for 'Making Nanoworld Comprehensible'
Courses and tutorials offered by professional societies	'Nanobootcamps,' The American Institute of Mechanical Engineering
International exchanges	Group visits by young scientists in Japan and EU
Nanomanufacturing processes, using a multimedia classroom integrated laboratory	University of Arkansas, in partnership with the states of Arkansas, Oklahoma and Nebraska
Education and analysis of societal implications of nanoscience and nanotechnoogy	'Social and ethical dimensions of nanotechnology,' University of Virginia 'Philosophical and social dimensions of nanoscale research: developing a rational approach to an emerging S&T,' University of South Carolina

training in nanobiotechnology is done via direct or indirect support by the National Institutes of Health, National Aeronautics and Space Administration, Department of Defense, Department of Energy and Environmental Protection Agency.

Future directions

The need for trained personnel will grow progressively from R&D and education to manufacturing and services, business and organizations. Here, states and regional nanotechnology alliances will play an increased role. Nanotechnology's success will not be determined only by fruitful research in academic and industry laboratories or by individual education programs, but by the creativity of individual researchers, the training of students in nanoscale science and engineering, connections between organizations, patent regulations, physical infrastructure, legal aspects, state and federal policies, and international cooperation.

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

Nanoscale science and engineering provides a common meeting place for many disciplines; not only does it focus our attention toward the same basic material structures, principles and tools of investigation, but it stimulates more fundamental research and education. Nanotechnology will require that a new world of knowledge be covered, and in different progression. Unifying science and converging technologies on this basis should be reflected in education. We envision reversing the current pyramid of learning that begins with specific techniques and formalisms in the first year of undergraduate studies and ends with a coherent understanding of physical and biological features.

In addition, addressing problem-driven, interdisciplinary education and training through interdepartmental collaborations needs to be considered. A systems approach may be included in teaching various aspects of nanoscale science and engineering.

The availability of sufficient scientists and industrial experts is uncertain if we continue on the current path. One may consider changes in the 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 is to ensure that 50% of US research institutions' faculty and students have access to the 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.

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