The Promises and Perils of Nanoscience and Nanotechnology: Exploring Emerging Social and Ethical Issues

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Rapid advances in nanoscience and nanotechnology are profoundly influencing the ways in which we conceptualize the world of the future, and human ability to manipulate matter at the atomic and molecular levels offers previously unimagined possibilities for scientific discovery and technological applications. The convergence of nanotechnology with biotechnology, information technology, cognitive science, and engineering may hold promise for the improvement of human performance at a number of levels. Based on a National Science Foundation–funded Research Experiences for Undergraduates Program in nanoscience and nanotechnology at the University of Central Florida (summer 2002), a variety of social and ethical issues associated with these advances is discussed. Implications for the future of science-technology-society studies and K-16 science education also are presented.

Keywords: *nanoscience, nanotechnology, ethics, science-technology-society, science education*

Introduction/Overview

Nanotechnology research is leading science into exciting and unknown frontiers in the new millennium. In 2001, the National Nanotechnology Initiative (www.nano.gov) was launched in the United States after having been approved by the U.S. Congress in November 2000 and funded for a total of $422 million for the 2001 fiscal year[1] (National Science Foundation, 2001, p. 1). This initiative and similar initiatives worldwide (e.g., in Australia, Canada, Europe, and Japan) have led to calls within the scientific community for concerted efforts to educate future scientists and the general public regarding ongoing developments in nanoscience and nanotechnology (Chang, 2002; Roco, 2002). By definition, nanoscience is the study of materials and associated physical, biophysical, and biochemical phenomena on the scale of ~1 to 100 nanometers. The National Institutes of Health (2000) described "nanotechnology" as involving

> research and technology development at the atomic, molecular, or macromolecular levels in the dimension range of approximately 1-100 nanometers to provide fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size.

The primary appeal of nanoscience (and attendant developments in nanotechnology) is the potential to create and manipulate matter at the nanoscale. This leads to the possibility of preparing novel materials (nanomaterials) that have specific, manipulable physical properties and functions. Such physical properties and functions include enhanced electrical and elec-

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tronic conductivities, lower thermal conductivities, and higher temperature deformation characteristics compared to their conventional bulk material counterparts.

Commentators such as Chang (2002) and Roco (2002) have suggested that future success in investigating systems at the nanoscale requires an increased focus on the role and scope of engineering education and, by extension, general science education. Allied with this sentiment are recommendations concerning the institutionalization of nanoscience and nanotechnology curricula in the K-12 education system and in the undergraduate curricula of colleges and universities. The highly interdisciplinary nature of nanoscience and nanotechnology research (and the desire to accelerate advancements in these areas) has led to the implementation of innovative partnerships integrating various lines of research and corresponding education efforts. The purpose of this article is to briefly describe one such initiative at the University of Central Florida (UCF), which received funding from the National Science Foundation (beginning summer 2002) to develop its Research Experiences for Undergraduates (REU) Program in Nanotechnology and Nanomaterials. Ultimately, the REU program will serve as the basis on which an undergraduate nanotechnology degree will be developed to prepare students for employment in the burgeoning fields of nanoscience and nanotechnology. One component of the summer 2002 program (the "ethics in nanoscience and nanotechnology" seminars developed and presented by the first author) will be highlighted here.

Nanoscience and Nanotechnology: Implications and Prognostications

As indicated by Mehta (2002), nanoscience represents a theoretical and procedural convergence of quantum physics, molecular biology/biochemistry, computer science, chemistry, and engineering. Technological innovations arising from nanoscience are likely to be commercialized as greater control over atom-by-atom and molecule-by-molecule construction occurs (p. 269). Examples of such anticipated innovations in a variety of areas include the following:

Environmental: Rebuilding the stratospheric ozone layer with the assistance of nanobots.
Medical: Developing techniques in nanosurgery; repairing defective DNA.
Electronic: Developing molecular circuit boards; improving the storage of data; developing molecular computers.
Materials science: Replicating valuable products (e.g. food, diamonds); improving the quality and reliability of metals and plastics (e.g., using various novel applications of carbon nanotubes); manufacturing "smart" materials (e.g., biomimetics, "shape memory" alloys). (Adapted from Mehta, 2002, p. 270)

In its comprehensive publication, *Societal Implications of Nanoscience and Nanotechnology,* the National Science Foundation (2001) suggested that

> among the expected breakthroughs [in nanoscience and nanotechnology] are orders-of-magnitude increases in computer efficiency, human organ restoration using engineered tissue, "designer" materials created from directed assembly of atoms and molecules, and the emergence of entirely new phenomena in chemistry and physics. (p. iii)

Continuing in this vein, the authors added that

> the effect of nanotechnology on the health, wealth, and standard of living for people in this century could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in the past century. (p. 2)

Clearly, anticipated advances in nanoscience and nanotechnology hold the promise of "big business." Over the next 10 to 15 years, projected global market turnovers of more than $1 trillion annually are expected in the areas of manufacturing, electronics, health care, pharmaceuticals, chemical plants, transportation, and environmental sustainability (pp. 3-4).

Of particular significance is the National Science Foundation's emphasis on the parallel exploration of emerging ethical and social issues associated with rapid developments in nanoscience/nanotechnology. The following sections of this article will present an overview of these issues in the context of the Nanomaterials Process and Characterization (NANOPAC) Program at UCF.

Program Description

Beginning in the summer 2002 semester, UCF received funding for the support of a 3-year REU site in NANOPAC, under the direction of Dr. Sudipta Seal (principal investigator) and Dr. Lucille Giannuzzi (co–principal investigator). The REU-NANOPAC site program was hosted in the Advanced Materials Processing and Analysis Center at UCF. The 10-week summer program (May 20-July 26, 2002, see http://nanotech.research.ucf.edu/nsf-reu/nanopac.htm) recruited 10 academically high-performing undergraduate students from across the country to participate in an intensive research experience on a wide range of nanomaterials topics, including applications in sensors, materials, optics, coatings, thin films, nanocharacterization, nanobiotechnology, and high-resolution transmission electron microscopy. Examples of specific projects included "Processing and Characterization of Carbon Nanomaterials" (evaluation of novel biomimetic methods for assembly of nanostructures and nanodevices), "Processing of Nanostructured Materials" (learning about mechanical alloying and process parameters for synthesizing nanomaterials/metrology), and "Nanostructured Polymeric Materials" (preparation and characterization of magnetic polymer nanocomposites).

Each student was paired with a university faculty member with ongoing research programs involving some aspect of nanomaterials development. Reflecting the interdisciplinary nature of research in nanoscience and nanotechnology, participating faculty members were drawn from the fields of engineering, physics, chemistry, and molecular biology/microbiology. The primary goal of the 10-week experience was to provide participating students with the opportunity to become actively involved with the respective faculty mentors' research groups. In addition, the participants were involved in extensive complementary educational activities, including a weekly seminar series focusing on their research projects, career development seminars, presentations by nanotechnology research and development guest speakers (e.g., U.S. Filter, Nanopowder Enterprises, Lockheed Martin, USNR, EEA Inc., Geltek), and field trips to local industries, research centers, and laboratories involved in nanotechnology development (e.g., Lockheed Martin, Disney, Geltek). Specialized seminars on "emerging ethical issues in nanoscience and nanotechnology" and "intellectual property protection and technological commercialization" also were presented by participating faculty. As a capstone to their REU experience, each student was required to prepare and give a presentation at a concluding poster session to UCF faculty and invited industry participants. With the assistance of their faculty mentors, REU students also were encouraged to present their research at professional conferences and subsequently to submit their research for publication consideration in appropriate academic journals. Formal evaluation of the program was undertaken by the first author of this article, details of which are provided elsewhere (Sweeney & Seal, 2003).

Socioethical Issues Associated With Nanoscience and Nanotechnology

The remainder of this article will highlight the structure and content of the "ethics in nanoscience/nanotechnology" seminars developed by the first author for the summer 2002 NANOPAC program.

Theoretical perspectives. Theoretical perspectives gleaned from the work of Mumford (1934/1963), Ellul (1967, 1980), Feenberg (1991), and Vanderburg (2000) were employed to develop a broad theoretical framework on which the design of the seminars was subsequently based. Although distinctive philosophical differences exist, the perspectives of these commentators may broadly be referred to as "critical theories" of technology, in which critical theory is defined here to mean processes or methods of social inquiry seeking to examine the ways in which technological development may inherently pose detrimental consequences to the wider society. In this context, a critical stance should not be interpreted as being one that is "antitechnology" or neo-Luddite; however, such a stance does advocate careful investigation and critique of technological advances to anticipate and perhaps ameliorate resulting negative sociocultural effects. Any modern technology is the product of a complex interplay between its designers and the larger society in which it develops (Pool, 2003). Science and technology are cultural artifacts (Mumford, 1934/1963) and, therefore, are subject to critiques in which issues of power, socioeconomic inequalities, and the development of technocratic elites are examined. It also should be noted that critical is not meant to indicate theories that examine only the negative. Critical theories seek to reveal the contradictions, underlying complexities, and tacit acceptance of social inequalities associated with dominant social agenda and the prevailing status quo; to this extent, they can be called negative. However, it might be more accurate to say that because critical theories run contrary to that which oppresses people, the theories usually are positive and hopeful (adapted from Nichols & Allen-Brown, 1996).

Mumford (1934/1963) argued that in spite of the reliance of technology ("technics") on the objective procedures of the sciences, technology itself is not an independent and value-neutral system or enterprise; "it exists as an element in human culture and it promises well or ill as the social groups that exploit it promise well or ill" (p. 6). According to Ellul (1967, 1980), technology perhaps is the most pervasive and potentially dehumanizing product of modern life. His "technological determinist" perspective suggested that the increasing ubiquity of technological applications to every aspect of modern human existence inevitably accompanied the growth of a "technological system" whereby human interactions and aspirations are increasingly shaped and mediated by technology. Ellul is perhaps most well known for his conception and critique of "la technique"; by "technique," Ellul did not refer simply to particular methods for employing a given technology "but the inexorable force of a technical way of thinking that threatens humanistic values" (Bruce, 1999). According to Ellul, technology ultimately acts to isolate people from each other and from the natural environment, and despite the (usual) benignity of its intended consequences, there always are unforeseen negative consequences. Most provokingly, Ellul (1980) also suggested that technological development will soon reach a point at which direct human control will no longer be necessary or possible (pp. 324-325).

Feenberg (1991) has articulated a "critical theory of technology" proposed as an alternative to what he describes as "established" theories of technology, that is, instrumental theory and substantive theory. As he discussed, the former treats technology as subservient to values established in other social spheres (e.g., politics or culture), whereas the latter attributes an autonomous cultural force to technology that overrides all traditional or competing values. Substantive theory claims that what the very employment of technology does to humanity and nature is more consequential than its ostensible goals (p. 5). According to Feenberg, the instrumental perspective tends to be the most widely held and accepted view of technology. Proponents of this perspective maintain that various technologies are merely "tools" designed and employed for specific purposes. From this perspective, technology in and of itself is seen as being "neutral" and free of overt ideological, cultural, social, or political biases. Those who adopt a substantive perspective argue that technology constitutes a new type of cultural system that restructures the entire social world as an object of control (p. 7), often in ways that are unanticipated. From this perspective, technology is not simply a means but has become an environment and a way of life, hence its "substantive" impact (p. 8). Feenberg's critical theory of technology posits that all technological development is shaped by ideological interests and that the everyday functions of contemporary society are predicated on a variety of complex interactions and relationships with technology. However, to transform or mediate the wider social implications of technology on society, one must learn to work from within the technology and the culture that it generates. In this manner, technology and technological development may be reshaped or influenced according to other ideological frameworks.

Vanderburg (1995, 1999, 2000) has proposed a "preventive approach" to technological development, characterized by careful examination of how current and emerging technologies influence human life, society, and the biosphere. With particular reference to the engineering disciplines, a preventive approach advocates the incorporation of societal issues into the study of engineering (Vanderburg & Khan, 1994; Young & Vanderburg, 1992) in which understandings of the interrelationships between technology, society, and the biosphere are employed in a negative-feedback mode to subsequently adjust technological design and decision making. Vanderburg (2000) indicated that conventional approaches to the design and implementation of modern technology are essentially nonpreventive and operate on three fundamental premises; that is, technology is separate from the society and the biosphere, its desired results are separate from the undesired ones, and technological values are separate from human values in assessing the results attained (p. 4). As Vanderburg pointed out, these premises are flawed because "there is no technology without a society, and no society without the biosphere" (p. 5).

Development of ethics seminars. Over the 10-week period of the summer 2002 program, five seminars (each of approximately 1.5 hours) were presented by the first author. The seminars were discussion based and emphasized active participation, debate, and, on occasion, spirited argument between the 10 REU students. Selected questions adapted from the Jacques Ellul Society's *Seventy-Six Reasonable Questions to Ask About Any Technology* (International Center for Technology Assessment, 2002) were used specifically to stimulate debate and analysis in the ethics seminars. The following questions were used:

Ecological: Does it preserve or reduce ecosystem integrity? How much, and what kind of waste, does it generate? Does it incorporate the principles of ecological design?

Social: How does it affect our way of seeing and experiencing the world? Does it serve to commodify knowledge or relationships? To what extent does it redefine reality?

Moral: What values does its use foster? What is gained by its use? What are its effects on the least advantaged in society?

Ethical: What does it allow us to ignore? Can we assume personal or communal responsibility for its effects? Can its effects be directly apprehended? What behavior might it make possible in the future? What other technologies might it make possible?

Political: Does it concentrate or equalize power? Does it require or institute a knowledge elite? Does it require military defense? Does it enhance or serve military purposes? How does it affect warfare? Is it consistent with the creation of a global economy? Does it empower transnational corporations? What kind of capital does it require?

Of the 10 students, 8 were materials science engineering or mechanical engineering majors, 1 student was a biochemistry major, and 1 student was a molecular biology/immunology major. Given the emphasis of the program (nanomaterials characterization and processing, housed in the UCF College of Engineering), the students were first introduced to definitions of "ethics in engineering," using Martin and Schizinger (1996) and Spier (2001) as primary source materials. Students were then asked to review and discuss selected professional engineering ethical standards from a variety of professional engineering organizations, including the Accreditation Board for Engineering and Technology (www.abet.org), the Institute of Electrical and Electronics Engineers (www.ieee.org), the National Society of Professional Engineers (www.nspe.org), and the American Society for Engineering Education (www.asee.org). Although the background for subsequent discussions in "nanoscience/nanotechnology ethics" was based on an initial review of professional standards and ethics pertinent to engineering, the material was presented in sufficient breadth so that the topics discussed were applicable across general science and engineering fields. Initial "general science/engineering ethics" topics included the following:

- Objectivity and subjectivity in science
- Value judgments in science, that is, "good," "bad," "right," "wrong," and so forth
- Merits of "basic" versus "applied" research
- Fabrication/falsification of data
- Data selection/manipulation
- Plagiarism
- Conflict of interest
- Authorship issues
- Mentoring issues
- Abuse of peer review process

No formal presentation of classic philosophical ethics (e.g., Aristotle, Kant, Locke, Mill, etc.) or of contemporary theories of technology (e.g., Mumford, Ellul, Feenberg, Vanderburg) was attempted in the seminars; however, various points of view relating to these perspectives were inevitably raised and discussed. Spier's (2001) synthesis of "ethical systems" (see below) was used to initiate discussions relating to current and anticipated developments in nanoscience and nanotechnological applications. Throughout the seminars, a science-technology-society (STS) approach was emphasized, which sought to have the students think critically and analytically about the roles of nanoscience and nanotechnology in society and the influence that their current and future research might have on future intersections of science, technology, and societal concerns (cf. Yager, 1990, 1996).

Ethical Systems

"Golden rule ethics": Do unto others as you would have others do unto you, or, its corollary, do not unto others what you would not wish others to do unto you. It may be related to a major principle of Kantian ethics; that is, you should only do that which you would wish to become a general practice for the society at large.

"Virtue/principle ethics": One should behave according to the dictates of one's conscience, emotions, desires, or instincts.
"Utilitarian ethics/consequentialism": The greatest good or greatest happiness for the greatest number.
"Eudaemonist ethics": Do what makes you or the community happiest. It may be related to a major principle of Aristotelian ethics; that is, the basis of all behavior is the goal of personal happiness.
"Survivalist ethics": Actions should be determined by that which most promotes self-survival and that of your family/tribe, other affiliated communities, or other biotic entities. (Adapted from Spier, 2001, pp. 73-77)

Specific social and ethical concerns in nanoscience/nanotechnology were broached by reviewing popular commentators in the field such as Richard Feynman (1959); K. Eric Drexler (1987, 1992), founder of the Foresight Institute (see www.foresight.org); Ray Kurzweil (1990, 1999, 2000); Bill Joy (2000); and Ralph Merkle (2001). Of particular interest was the students' passionate involvement in seminar discussions addressing possible military applications of nanotechnology research, which is perhaps not surprising given the tragic events of September 11, 2001, in New York City. Available details of current requests for proposals issued by the U.S. Department of Defense and funded research programs with explicit military applications (e.g., "Nanotechnology for Energetics and Warheads," "Smart Coatings," and the Institute for Soldier Nanotechnologies at the Massachusetts Institute of Technology) were obtained by the first author and discussed in the seminars.

Subsequent discussions of ethical and societal implications also explored how advances in nanoscience and nanotechnology might influence or affect national and global economics, environmental sustainability, the development of pharmaceuticals, human life span and quality of life, and education/workforce preparation. More philosophically oriented ethical questions that were explored included the following:

- Intellectual property: Who "owns" this knowledge?
- University-industry-government relationships (e.g., Gibbons et al., 1994; Leydesdorff & Etzkowitz, 1996): Who funds what?
- Informing the general public: To what extent?

Although no formal pre– or post–student attitudinal evaluations were undertaken in the summer 2002 ethics seminars,[2] it appeared that a number of useful perturbations had been occasioned by the issues raised and discussed with the first author. Although students appreciated the obligation of scientists and engineers to behave ethically in the procedural conduct of their research, there seemed to be a level of reluctance to consider the responsibility of scientists/engineers for the resulting "good" or "bad" uses and applications of such research. In response to the first author's suggestion that science and technology (broadly defined) could not be divorced from issues of culture and social policy, several students commented that their interests lay in science and engineering as rewarding intellectual pursuits and that they were much less interested in the "messy" political ends to which their research findings might be deployed. Although a comprehensive theoretical analysis of these student attitudes in terms of instrumental, substantive (Feenberg, 1991), preventive, and nonpreventive (Vanderburg, 2000) perspectives falls outside the scope of the present commentary, this provides an intriguing and important area of inquiry that may lead to further understanding of how future scientists and engineers develop their professional belief systems, which subsequently act to inform and guide their professional scientific endeavors. Interestingly, of the 10 students (3 female, 7 male), the female students appeared to be more willing than a majority of the male students to consider the political/social repercussions of advances in nanoscience and nanotechnology. Although this may suggest some gender-based differences, this remains speculative at the present time and may merit further study. All students, however, agreed that the seminar series on ethical issues in nanoscience and nanotechnology had prompted them to think more widely about the social implications of such advances than they otherwise might have. This is a modest but important outcome:

> While there is no way of knowing, *a priori*, the unintended and higher order consequences of nanotechnology, the participation of social scientists [and science educators] in the National Nanotechnology Initiative may allow for important issues to be identified earlier, the right questions to be raised, and necessary corrective actions taken. (National Science Foundation, 2001, p. 12)

More recently, Mnyusiwalla, Daar, and Singer (2003) have suggested that advances in nanotechnology will be derailed if serious study of nanotechnology's ethical, environmental, economic, legal, and social implications does not maintain pace with progress in the science (p. R9). This provides a significant impetus for continuing our efforts to expose future scientists and engineers to these issues.

Concluding Comments

With regard to advances in nanoscience/nanotechnology and the ethical issues associated with those advances, the concluding section of this article offers some speculative thoughts concerning implications held for the future of STS studies and for K-16 science education.

Implications for the future of STS studies. STS researchers with an interest in nanoscience and nanotechnology will need to establish closer professional links with chemists, physicists, biologists, and engineers who are conducting various lines of nanotechnology research. How and to what extent are major research institutions incorporating "ethics of nanotechnology" classes or modules into their undergraduate science/engineering education curricula? What are the views of nanotechnology researchers themselves with regard to the social and ethical implications of their work? How will social and ethical implications of nanotechnology research be communicated most effectively to the general public?

Significant opportunities also present themselves for fruitful STS inquiry in terms of the many social/ethical issues now being considered as a result of the Human Genome Project. How do social/ethical issues in nanoscience and nanotechnology overlap with concerns related to genetic engineering and cloning? Which sections of society have access to these new technologies, and who ultimately runs the risk of being economically and socially disenfranchised or disadvantaged as a result of these developments (see, for example, Boylan & Brown, 2001; Brannigan, 2001; Dhanda, 2002; Mnyusiwalla et al., 2003; Reynolds, 2002)?

In addition to the potential effect on global economics (even greater demarcations between the world's "haves" and "have-nots"), other hitherto "futuristic" scenarios also need to be considered. Technological advances are now at the stage in which functional interfaces between computers and the human brain (mind?) are now being seriously discussed. Will it be possible within the next 50 to 100 years (or sooner) to "store" and "download" a person's memories and experiences? Will computers eventually become sentient (see, e.g., Kurzweil, 1990, 1999)?

> In the area of cognition, revolutionary technical advances could have great impact on individual productivity and independence. We do not understand the workings of the brain well enough to predict with any confidence that assistive devices will actually work. However, rapid advances in the intersecting nano-, information science, and biological sciences seem to promise significant surprises. Possible results include devices that enhance learning, cognition, judgment and decision making. Devices that helped people with dementia—nearly a third of the population over 85—could have great impact. At the same time concerns about the use of artificial or assisted cognition for social control must be addressed. (National Science Foundation, 2001, pp. 41-42)

> The convergence of nanotechnology, biotechnology, information technology and cognitive science could create new scientific methodologies, engineering paradigms and industrial products that would enhance human mental and interactive abilities. By uniting these disciplines, science would become ready to succeed in a rapid program to understand the structure and functions of the human mind, *The Human Cognome Project*. Truly, the mind is the final frontier, and unraveling its mysteries will have tremendous practical benefits. Among the most valuable spin-offs will be a host of devices that enhance human sensory capabilities. We will be able to build a vast variety of humane machines that adapt to and reflect the communication styles, social context, and personal needs of the people who use them. We will literally learn how to learn in new and more effective ways, revolutionizing education across the life span. New tools will greatly enhance creativity, industrial design, and personal productivity. Failure to invest in the necessary multidisciplinary research would delay or even prevent these benefits to the economy, to national security, and to individual well-being. (National Science Foundation/U.S. Department of Commerce, 2002, p. 85)

Implications for the future of K-16 science education. In any informed consideration of social/ethical issues associated with scientific and technological advances, education plays a vital role. Within the next 5 to 10 years, it seems inevitable that suitably modified content material emerging from ongoing research in nanoscience and nanotechnology will eventually "filter down" and become incorporated in formal science instruction at the K-12 level. Clearly, science teachers at all levels need to be made aware of these developments and adequately prepared so that they are able to teach about these advances in a developmentally appropriate manner. An anticipated challenge might be that of science teachers' perceptions of their professional responsibilities: Is their role solely to teach science content, or should they also be concerned with the political, social, and cultural dimensions of science teaching (e.g., Sweeney, 2001)? Issues relating to general/public scientific literacy become an even more pressing concern, given the extent to which these new technologies are expected to affect all aspects of human experience. The very process of learning (and learning to learn) might change in the manner described below:

> In the future, everyone will need to learn new skills and fundamental knowledge throughout life, often in fields connected to mathematics, engineering, and the sciences. Thus we will need new kinds of curricula, such as interactive virtual reality simulations run over the Internet that will allow a student anywhere to experience the metabolic processes that take place within a living cell, as if seeing them from a nanoscale perspective. New, dynamic ways to represent mathematical logic could be developed based on a correct understanding of how the human mind processes concepts like quantity and implication, allowing more people to learn mathematics more quickly, thoroughly, and insightfully. The social interaction resulting from multiuser video games can be harnessed as a strong learning motivator, if they are designed for the user's demographic and cultural background and can infuse the learning with mystery, action, and drama. The goal would be to revolutionize science, mathematics, and engineering education through experiences that are emotionally exciting, substantively realistic, and based on accurate cognitive science knowledge about how and why people learn. (National Science Foundation/U.S. Department of Commerce, 2002, p. 87)

For science education as a discipline, implications exist for refining our understandings of how conceptual change occurs (cognitive theories) and our understandings of science misconceptions or naive conceptions. How, for example, will future science education research conceptualize the behavior of matter and the ways in which matter may be manipulated? What will be the wider implications for science teaching and learning?

At the undergraduate level, introductory science classes and "science for nonmajors" classes also may be expected to undergo marked changes. At UCF, for example, plans are underway to develop a stand-alone "ethics in nanotechnology" course for nonscience/nonengineering majors, in addition to an interdisciplinary undergraduate degree program in nanoscience and nanotechnology. Future goals are to use what we have learned so far in designing the program described here to make the content and concepts adaptable for K-12 science teaching and learning. Much remains to be accomplished, and much remains to be learned. We indeed live in exciting times.

Notes

1. The fiscal year 2003 president's budget request of about $710 million for federal investment in nanoscale science, engineering, and technology represents a 17% increase over fiscal year 2002. Additional budget details may be accessed at http://www.nano.gov/2003budget.html.

2. As the authors further develop a research agenda in the area of ethical issues associated with developments in nanoscience/nanotechnology, appropriate instruments for measuring levels of related attitudinal change/ethical awareness will be sought and/or developed.

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