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Social and Ethical Dimensions of Nanoscale Science and Engineering Research

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ABSTRACT: *Continuing advances in human ability to manipulate matter at the atomic and molecular levels (i.e. nanoscale science and engineering) offer many previously unimagined possibilities for scientific discovery and technological development. Paralleling these advances in the various science and engineering sub-disciplines is the increasing realization that a number of associated social, ethical, environmental, economic and legal dimensions also need to be explored. An important component of such exploration entails the identification and analysis of the ways in which current and prospective researchers in these fields conceptualize these dimensions of their work. Within the context of a National Science Foundation funded Research Experiences for Undergraduates (REU) program in nanomaterials processing and characterization at the University of Central Florida (2002-2004), here I present for discussion (i) details of a "nanotechnology ethics" seminar series developed specifically for students participating in the program, and (ii) an analysis of students' and participating research faculty's perspectives concerning social and ethical issues associated with nanotechnology research. I conclude with a brief discussion of implications presented by these issues for general scientific literacy and public science education policy.*

INTRODUCTION

> *Science is the creation of scientists, and every scientific advance bears somehow the mark of the man who made it. The artist exposes himself in his work; the scientist seems rather to hide in his, but he is there.*
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> *The truth of the matter is that the creative scientist, whatever his field, is very deeply involved emotionally and personally in his work, and that he himself is his own most essential tool.*[1(p.456)]

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Despite the overtly gender-biased language that was quite acceptable in public discourse four decades ago, the above quote very aptly captures the essence of what I wish to discuss in this forum. As human enterprises, science, engineering and all forms of technological development are suffused with our idiosyncratic moral conceptions of “right”, “wrong”, and of what constitute socially acceptable or unacceptable endeavors. While scientific research exemplifies the application of human creativity in many and varied forms, the doing of science also provides the opportunity to express a range of human frailties and fallibilities.[2(p.22)] Halfway through the first decade of the 21st century, advances in the rapidly developing constituent fields of nanoscale science and engineering (hereafter somewhat loosely referred to as “nanotechnology”) have captured the public imagination, in large part because of mounting speculations regarding the social and ethical implications of nanotechnology research.[3,4,5] Paralleling these advances is the increasing realization by those in the science and engineering education community that a number of associated social, ethical, environmental, economic and legal dimensions also need to be explored. An important component of such exploration entails the identification and analysis of the ways in which current and prospective researchers in these fields conceptualize these dimensions of their work.

I will structure the ensuing discussion concerning these issues in three sections. The first section will provide definitions and some technical background regarding nanotechnology. Here, I also will provide an overview of the primary governmental organization that is responsible for coordinating the development of nanotechnology research in the U.S., i.e. the *National Nanotechnology Initiative* (www.nano.gov). One of the currently stated goals of the organization implicitly addresses the exploration of social and ethical dimensions of the underlying research, which provides the framework for the discussion.

The second section provides the context of my recent work in this area, and the empirical basis for this paper. As a participating faculty member in a 3-year National Science Foundation funded *Research Experiences for Undergraduates* (REU) program in nanomaterials processing and characterization at the University of Central Florida, one of my primary responsibilities included the development and implementation of a series of seminars addressing “social and ethical issues associated with nanotechnology research.” Details of the seminar series (i.e. its conceptual development and major instructional components) are presented, with the goal of stimulating discussion and critique from readers of the journal. During the final year of the initial 3-year program (Summer 2004), I conducted a brief study that attempted to examine the perspectives of participating undergraduate students and nanotechnology research faculty. The methodological approach, major findings and analyses are presented.

In the third section, I advance some recommendations and a few speculations for future inquiry attempting to further explore the social and ethical dimensions of nanotechnology research. I conclude by offering a few comments regarding the implications of ongoing nanotechnology research for general scientific literacy and public science education policy.

Defining "nanotechnology"

"Nanoscience" is the study of materials and associated physical, chemical, biophysical and biochemical phenomena on the scale of ~1-100 nanometers. Kelsall, Hamley and Geoghegan[6] define nanotechnology as being "the term used to cover the design, construction and utilization of functional structures with at least one characteristic dimension measured in nanometres."[6(p.1)] The primary appeal of nanoscience (and resulting technological applications) is the potential to control and manipulate matter at the nanoscale. This leads to the possibility of preparing novel materials (nanomaterials) that have specific physical properties, and "implies the capability to build up tailored nanostructures and devices for given functions by control at the atomic and molecular levels."[7(p.2)] Such physical properties and functions include enhanced electrical and electronic conductivities, lower thermal conductivities and higher temperature deformation characteristics compared to their conventional bulk material counterparts. It now has been demonstrated that many important characteristics of matter depend on the size of nanoscale particles, including magnetic properties, optical properties, melting points, specific heat capacities and surface reactivities.[8] At this nanoscopic scale, matter behaves according to the probabilistic laws of quantum mechanics and other unique physical properties. Accordingly, established theories of matter will have to be refined in order to explain previously unencountered physical phenomena at the nanometer level.[8-12] As Mehta[13] observes, "nanotechnology" is an umbrella term for a wide range of technologies, and, of particular significance, represents a convergence of quantum physics, molecular biology, computer science, chemistry, and engineering.[13(p.269)] However, use of the term "nanotechnology" as an all-encompassing reference for a range of science and engineering research activities that investigate matter at the nanoscale has led to intense debate between researchers about what actually is meant, implied and understood by the term. Particulars of the debate will not be recapitulated in detail here, however readers are encouraged to review some of the most salient recent commentaries.[14-22] For the purposes of this discussion, it is important to understand that science and engineering research at the nanoscale may be conducted using either "top-down" or "bottom-up" approaches. The top-down approach (i.e. manufacture of nanoscale structures by various lithographic, machining, etching or chemical vapor deposition techniques) currently dominates research activities in the field. This approach is typified in the terms "nanoscale technology" or "incremental nanotechnology". However, in its original sense (as presaged in Richard Feynman's[23] famous 1959 lecture at CalTech), "nanotechnology" refers to a bottom-up approach, i.e. the manufacture of organic and inorganic structures atom-by-atom or molecule-by-molecule. Bottom-up nanotechnology (also variously described as "advanced nanotechnology", "molecular nanotechnology", "transformative nanotechnology" or "radical nanotechnology") is a much more ambitious and (currently) rather less well-developed approach.[a] Although it has been argued that conflation of the two approaches in the umbrella term "nanotechnology" is misguided

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a. For an excellent examination of the underlying scientific principles and methodological merits/demerits of top-down and bottom-up approaches in nanotechnology research, see "*Soft Machines: Nanotechnology and Life*",[20] by Richard A. L. Jones (2004).

and complicates attempts to develop appropriate policy decisions,[21] for the most part, I will continue to use the umbrella term here and specify the distinction where appropriate.

While the preceding definitions all focus primarily on details pertaining to physical characteristics and dimensions, metrology, and approaches in the manufacture of nanomaterials, it is the definition offered by my colleague Rosalyn Berne[24] that allows us to begin thinking in a more focused manner about the ways in which nanotechnology research may indeed be associated with a variety of social and ethical dimensions. According to Berne, nanotechnology may be defined as "the emerging capability of human beings to observe and organize matter at the atomic level."[24(p.627)] and "nanoscale[d] science and technology" may be characterized as a pursuit involving "the study, control, manipulation and assembly of multifarious nanoscale components into materials, systems and devices to serve human interests and needs."[24(p.628)] While we can acknowledge the existence of several essential, "universal" human interests and needs (such as the physiological need for food, water and shelter represented at the lowest level of Maslow's Hierarchy of Needs,[25,26] beyond these necessary basics, the concept of "human interests and needs" is one that has been subject to considerable analysis.[27,28] Individually and collectively, many of our most intensely defended interests and important needs (whether actual or perceived) correlate highly with our respective standings in various socioeconomic and power structures, level of formal education, political views, religious views, etc. Conceptions of what constitute "human interests and needs" address in a very fundamental manner our definitions of what it means to be human, and ultimately, our individual and collective visions for the world of the future.

Turning now to the U.S. National Nanotechnology Initiative and its extensive research agenda, what are considered to be the primary interests and needs? Do these stated interests and needs indicate particular social and ethical issues that are important to explore?

The U.S. National Nanotechnology Initiative: identifying pertinent social and ethical issues

In 2001, the National Nanotechnology Initiative (NNI) was launched in the USA after having being approved by the U.S. Congress in November 2000, and funded for a total of $422 million for the 2001 fiscal year.[29] By the 2004 fiscal year, federal funding for the NNI had more than doubled to approximately $961 million.[30] At time of writing, federal funding for the NNI in the 2006 fiscal year is expected to exceed $1 billion.[b] Similar initiatives worldwide (e.g. in Australia, Canada, China, Europe, India and Japan) also are investing heavily in fundamental nanotechnology research, in addition to associated education and commercial development activities.

b. Current budget details for the U.S. NNI may be accessed at: http://www.nano.gov/html/about/funding.html.

Currently,[c] the four stated goals of the NNI are to: (1) *maintain a world-class research and development program aimed at realizing the full potential of nanotechnology*; (2) *facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit*; (3) *develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology*; and (4) *support responsible development of nanotechnology*. Whether the goals of the NNI are ranked in order of perceived importance or priority remains open to speculation. We also may speculate about why the NNI chose to reword its goals in such a way that no longer directly highlights the phrase "social, ethical, environmental and health implications of the new technology", choosing instead to collapse these very specific terms into the rather blandly stated objective of "support responsible development of nanotechnology". Nevertheless, it is important to acknowledge that from its inception, the NNI consistently has emphasized the parallel exploration of emerging social and ethical issues associated with rapid developments in nanotechnology research.[d] Later in my discussion, I will suggest a reason for the adoption of this approach.

In what I consider to be a particularly important article describing his views of what constitute "the broader societal issues of nanotechnology", Mihail Roco[31] (Chair of the U.S. National Science and Technology Council's subcommittee on Nanoscale Science, Engineering and Technology; Senior Advisor for Nanotechnology at the U.S. National Science Foundation; and a key figure in the NNI) indicates that "[t]he main reason for developing nanotechnology is to advance broad societal goals such as improved comprehension of nature, increased productivity, better healthcare, and extending the limits of sustainable development and of human potential."[31(p.181)] Subsequent comments in the article begin to identify broad areas in which emerging social and ethical issues are deemed to be important:

> Societal implications of nanotechnology *apply in a variety of areas*, including technological, economic, environmental, health, and educational, ethical, moral and philosophical. While technological and economic implications are the key drivers, issues about the unexpected positive and negative consequences of nanotechnology are competing in the other areas.[31(p.185)]

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c. The goals indicated above were accessed in May 2005 at http://www.nano.gov/html/about/home_about.html. While drafting an initial outline of this paper in November 2004, I accessed the same website, at which time, the goals read as follows: (1) *conduct research and development to realize the full potential of this revolutionary technology*; (2) *develop the skilled workforce and supporting infrastructure needed to advance research and development*; (3) *better understand the social, ethical, health and environmental implications of the technology*; and (4) *facilitate transfer of the new technologies into commercial products*.

d. Information regarding the "*Societal Dimensions Program Component Area*" of the NNI may be accessed at http://www.nano.gov/html/society/home_society.html. Projected funding for the 2006 fiscal year is approximately $82 million, including $39 million for programs directed at environmental, health and safety research & development, and $43 million for education-related activities and research on the broad social and ethical implications of advances in nanotechnology. The allocation represents just under 8% of total expected NNI funding of approximately $1,054 million for the 2006 fiscal year.

In an earlier publication sponsored by the National Science Foundation[29] (entitled *Societal implications of nanoscience and nanotechnology* and co-edited by Mihail Roco and William Sims Bainbridge), it is 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."[29(p.iii); e] Even more notably, it now is being increasingly predicted that the convergence of nanotechnology, biotechnology, information technology and cognitive science will affect all aspects of human experience,[29,32-35] with prominent scientists such as Carlo Montemagno[36] suggesting that the application of this integrative technology "will significantly improve the human condition."[36(p.47)]

It is clear that many "social and ethical issues" are implied in the articulation of these interests, aspirations and predictions. We may, for example pose the following questions: by what (and by whose) criteria is "improvement of the human condition" being defined? Might the directed assembly of "designer" materials have unexpected effects (beneficial or otherwise) on the biosphere? How might development and applications of these novel technologies ultimately influence human behavior and interactions? However, in a manner similar to the debate on how the term "nanotechnology" ought properly to be defined, what is meant, understood and implied by the term "social and ethical issues" also is not without the need for clarification. Schummer[37] points out that use of the term "social and ethical issues" means different things to different constituencies, depending on respective interests, goals and motivations. As he discusses in his analysis, scientists and engineers engaged in nanotechnology research tend to think about "societal implications" primarily in terms of the tangible technological applications of their work. For environmental scientists and toxicologists, considerations of these implications largely are framed as potential risks to human health and to the wider environment. Policy-makers and science managers (e.g. upper-level administrators of large governmental organizations such as the NNI) frequently associate "societal and ethical implications" with education and economics, allied with the notion of national progress and global leadership. Yet another group, cultural and social scientists, conceptualize "societal and ethical implications" of nanotechnology research largely in terms of the influences that development of nanotechnology research have on society and *vice versa*. Perhaps somewhat contentiously, Schummer argues that the latter is a more sophisticated meaning of the term than those held by the other groups identified in his analysis.[f] In a companion publication, Lewenstein[38] identifies the underlying principles that define "social and ethical issues" in nanotechnology research, and also makes an important

e. As an aside, it ought to be noted that the examples cited here suggest future expected advances primarily in "bottom-up" nanotechnology.

f. My own conceptions of what constitute "social and ethical issues" in nanotechnology research are a blend of Schummer's characterizations for scientists and for cultural/social scientists. Clearly, this presents implications for the manner in which I present and examine these issues with students/prospective nanotechnology researchers, and this is discussed in more detail below.

distinction between the terms "social and ethical issues" and "societal and ethical implications". According to Lewenstein, the latter phrase suggests that science and technology are followed by resulting "implications", and as he correctly observes, the documented history of scientific and technological development does not support this perspective. Lewenstein draws attention to the fact that the commonly cited areas in which nanotechnology research is likely to have potential implications (e.g. the habitable environment; the workforce; individual privacy; national and international politics; intellectual property; human enhancement) all portend emerging *social* issues since they all affect the extent and quality of human interactions and relationships. In addition to being social issues, they also engender *ethical* issues since they all connote conceptions of "moral" or appropriate behavior, and as Lewenstein states, "all involve questions of fairness, equity, justice, and especially power in social relationships." It is important to note, as does Lewenstein, that such social and ethical issues are not specific to *nano*technology alone; *any* modern technology is the product of a complex interplay between its designers and the larger society in which it develops.[39] Science and technology are cultural artifacts and therefore, are subject to critiques in which issues of power and potential inequities are examined.[40]

Having provided a cursory overview of the NNI, its stated interests, and also a summary of the major social and ethical issues associated with developments in nanotechnology research, it is useful at this point to briefly consider a primary reason underlying the organization's motivation to explore social and ethical issues in conjunction with the ongoing research and technological development. It may be argued that the adoption of this approach is a focused attempt to pre-empt public "backlash" or "resistance"[41] similar to that which occurred with genetic engineering and bioengineering in the 1970s-1990s, particularly so in Europe (and to a lesser extent in the U.S.) with respect to genetically modified organisms and foods.[42-44; g] A number of commentators (including Wolfson,[48] Mehta,[49] and Einsiedel & Goldenberg[50]) provide support for this perspective, and suggest that in order to effectively address emerging social and ethical issues associated with nanotechnology research, those in the nanotechnology research community ought to pay close attention to past lessons learned in terms of public reaction to biotechnology research. In what might be assumed to be a reference to such past public reaction, a statement in the executive summary of the National Science Foundation document to which I referred earlier[29] proposes that "sober, technically competent research on the interactions between nanotechnology and society will help mute speculative hype and dispel some of the unfounded fears that sometimes accompany dramatic advances in scientific understanding."[29(p.iii)]

However, as Pilarski et al[51] note, there is, at present, a considerable discrepancy between our "nanotechnological capabilities", and general consensus on how to apply our "social wisdom" to address important emerging social and ethical issues. A "grand

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g. For extensive commentary and analysis regarding "social/ethical issues" and public concerns associated with biotechnology/genetic engineering, see, for example, Fukuyama[45], Fumento[46] and Magill.[47]

challenge"[52] will be that of encouraging prospective and current nanotechnology researchers to engage – in a thoughtful and critical manner – with these issues as an integral part of their research endeavors. In the following sections, I present a description and subsequent analysis of my recent efforts in this area.

Exploring Social and Ethical Issues in Nanotechnology Research: The NANOPAC-REU Program at the University of Central Florida

The focus of my discussion in this forum occurs in the context of a National Science Foundation funded *Research Experiences for Undergraduates* program in *Nanomaterials Processing and Characterization* (NANOPAC-REU) offered at the University of Central Florida over the course of three discrete 10-week summer periods, 2002-2004, respectively. The REU program[53] is an important component of the National Science Foundation's mandate to improve the quality of science, technology, engineering and mathematics (STEM) education in the U.S. Academically able students in these disciplines are specifically targeted for participation in a variety of REU offerings by different universities, and resources are provided that allow these students to participate in undertaking original research under the supervision of university faculty. The focus of the program on exposing undergraduate students to research aligns with national goals to produce a greater number of well-prepared STEM professionals who eventually will contribute to the advance of knowledge in various STEM disciplines (academia/industry) and STEM education.[54] The NANOPAC-REU program also complemented a major recommendation of the NNI, i.e. that exposure to various areas of nanotechnology research ought to occur at the undergraduate level so that these students begin to develop the requisite interdisciplinary knowledge, skills and perspectives for successful future research in the field.

Comprehensive details relating to the overall NANOPAC-REU program structure and evaluation may be found in previous publications,[55,56] and interested readers are invited to peruse the program website for additional information (see http://nsfreunano.research.ucf.edu/index.html). In addition to the intensive 10-week focus on various aspects of nanotechnology research, undergraduate students also participated in a number of complementary program seminars, one of which was designated "ethics in nanotechnology research". My involvement in the NANOPAC-REU program was in a dual capacity, i.e. as the internal program evaluator, and also as the "education person" who developed and presented the seminars on "ethics". Although not having a formal academic background in ethics or ethical theory beyond an undergraduate course many years ago in "classic" philosophical ethics and my own extensive reading in subsequent years, as a science education professor, my approach to designing the seminars deliberately incorporated three related perspectives. Briefly stated, these were (i) science and engineering are not value-free activities divorced from human goals, interests, motivations and desires;[57-60] (ii) discussion of social and ethical issues pertaining to science and technology is best undertaken using a Science-Technology-Society (STS) pedagogical approach, in which the three components are demonstrated to be interdependent and to mutually affect and influence each other;[61, 62] and, (iii) as much as possible, one needs to use actual examples from science and engineering research (as opposed to an almost exclusive reliance on hypothetical scenarios) in order to exemplify how considerations of social and ethical issues are both applicable and pertinent to the overall professional education of future scientists and engineers.

Five seminars per summer program on "social and ethical issues in nanotechnology research" were developed and presented. As I have described elsewhere,[55,56] the seminars were discussion-based, and emphasized active participation, debate (and on occasion, spirited argument) between the REU students. Students first were introduced to definitions of "ethics in engineering", using Martin and Schinzinger[63] and Spier[64] as primary source materials. Students then were 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 pertaining to "ethics in nanotechnology research" 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. No formal presentation of classic philosophical ethics (e.g. Aristotle, Kant, Locke, Mill, etc.) or of contemporary theories of technology (i.e. Mumford;[40] Ellul;[65,66] Feenberg;[67] Vanderburg[68]) was attempted in the 2002 seminar offerings, although explicit discussion of contemporary theories of technology was incorporated into the 2003 and 2004 seminars. Spier's synthesis of "ethical systems"[64(pp.73-77)] and selections from Ellul's "*76 reasonable questions to ask about any technology*" (see http://www.thewords.com/articles/ellul76quest.htm) were used to initiate discussions relating to current and anticipated developments in nanotechnology research.

During the Summer 2002 seminars, focus was given to examples of potential social and ethical issues associated primarily with "bottom-up" or molecular nanotechnology, such as self-replicating nanomachines, nanoassemblers, disassemblers, and the infamous "gray goo scenario", suggested by K. Eric Drexler in *Engines of Creation*[14] and popularized in Michael Crichton's science fiction novel, Prey.[69; h] Although these topics generated animated discussion between the REU students on the various *pros* and *cons* of molecular nanotechnology, such examples were somewhat incongruous with their research projects which focused mainly on the processing and characterization of various nanomaterials using conventional "top-down" manufacturing techniques. Modifications were made to the design of the 2003 and

h. The likelihood – or necessity – of an occurrence of the "gray goo scenario" has since been repudiated; see, for example, Drexler[18] and Phoenix and Drexler.[70]

2004 seminars so that consideration and analysis of "social and ethical issues" were linked more closely to the actual nanotechnology research projects being undertaken. Below, I discuss in more detail the structure of the ethics seminars developed and offered in the Summer 2004 program, and also provide an overview of the study conducted during that semester.

Specifics of the Summer 2004 seminars

As mentioned above, particular attention was paid to the design of the 2003 and 2004 ethics seminars so that discussion of potential social and ethical issues related more closely to the students' actual nanotechnology research projects. Examples of actual projects that were particularly amenable to an analysis of potential social and ethical issues included *nanostructured biomaterials* (issues related to biomedical implants and potential human enhancement); *performance of solid rocket propellants with nanoparticle additives* (issues related to the development of space program and military applications); and *processing and characterization of carbon nanomaterials* (related to other efforts nationally and internationally to produce carbon nanomaterials in bulk, although concerns have been raised about the largely unknown biological/environmental effects of mass produced carbon nanomaterials[i]).

Subsequent discussions of social and ethical implications also explored how advances in nanotechnology research might influence or affect national and global economics; environmental sustainability; the development of pharmaceuticals; human lifespan 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 (*who funds what, and why?*);[73-76] and, informing the general public (*to what extent?).* Three topics were noted to be of particular interest to the students, i.e. *implications of the Bayh-Dole Act on funding opportunities and research priorities in nanoscale science and technology*; *nanotechnology for military uses*; and *environmental sustainability/biotoxicity of nanomaterials*.

Discussions relating to the Bayh-Dole Act[j] addressed its potential "unintended effects" such as skewing the direction and priorities of research, and restricting the timely dissemination of research findings due to considerations of patent

i. Much more attention has been given in Europe to these kinds of concerns than currently appears to be the case in the U.S.; see, for example, Helland[71] and the Royal Society and the Royal Academy of Engineering.[72]

j. The *Bayh-Dole University and Small Business Patent Procedures Act* was legislated by the U.S. Congress in 1980. As a result of the Act, U.S. universities are allowed to retain ownership to discoveries and inventions realized from federally (i.e. publicly) funded research. Reciprocally, universities are expected to file for patent protection and to ensure commercialization of discoveries and inventions upon licensing.[77-80] Royalties are shared between the researcher/s and the university, and a percentage of the income generated from commercialization is reinvested into the technology transfer process. As a pertinent example, in November 2004, the UCF Office of Research quietly announced that it now would be known as the Office of Research & Commercialization.

confidentiality.[77-79] Related to these discussions were those in which contentious questions were posed concerning what many university faculty now characterize as the undue "commercialization" of the university and the influence exerted on university research and teaching activities by external business and commercial interests.[81-86] Given the elevated levels of funding currently being allocated to nanotechnology research in the U.S. and the highly competitive nature of entrepreneurship often accompanying such research efforts, Gibbons *et al.'s*[73] analysis of the dynamics of modern day scientific research provides a particularly useful model for framing these issues in undergraduate nanotechnology research and education. Recent commentators such as Mazzola[87] and Paull *et al.*[88] note that while commercial nanotechnology is still in its infancy and will require a concerted and sustained effort to convert basic science research discoveries into mass marketable products, the rate of technology enablement is increasing. Given that research in nanoscale science and technology now is integral to corporate research and development across a wide range of industries, business models within the "triple helix" of academia-industry-government relations[75] will need to evolve and change because of nanotechnology's anticipated impact in the marketplace and wider global economy.

Discussions relating to potential military uses of nanotechnology[89-91] first introduced students to various nanotechnology-related projects at UCF funded by the U.S. Department of Defense (www.defenselink.mil), and the U.S. Defense Advanced Research Projects Agency (www.darpa.gov) with applications pertinent to branches of the military (Army, Navy and Air Force), and also to other similarly funded projects in the U.S. such as the *Institute for Soldier Nanotechnologies* at the Massachusetts Institute of Technology (http://web.mit.edu/isn/). This topic, in particular, engendered several vigorous discussions between students that were overtly political in nature, and led to various comments such as "*the need to maintain the global superiority of the U.S.*", "*U.S. trade and economics are based on a strong military presence and the proliferation of a global free market economy*", and "*the subversion of science by warmongers*". Related student commentary also addressed the *pros* and *cons* of the "big stick" policies characteristic of the Cold War, and the fact that funding and development of science and technology often are spurred by considerations of military defense and/or offense. As the professor leading the seminars, I was careful to ensure that all opinions and perspectives were accorded validity, whatever my own political opinions on the matter. This is an important consideration for other science and engineering educators who may wish to adapt some elements of the approach described here. Perhaps even more so than the other topics addressed during the seminars, discussion of the potential military applications of nanotechnology research led to the most "emotional" student engagements, and emphasized particularly well to them that they likely would face the decision of considering these "social and ethical" issues in their work (or not) as future researchers. It was interesting to note, as does Newberry,[92] the comments of several students who indicated that one reason why they decided to pursue science and engineering as careers in the first place was to avoid having to worry about these types of "messy", emotionally charged issues. Over the course of the three initial summer programs 2002-2004, I noted that in general, female students appeared more willing than male students to consider the political, social and ethical repercussions of advances in nanotechnology, particularly with respect to potential military applications. While this may suggest some gender-based differences, this remains speculative at the present time, and may merit further study. This and similar issues provide an intriguing and important area of inquiry which 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.[93]

Discussions in the seminars pertaining to environmental sustainability focused initially on distinguishing between "nanoscale science and technology" and "molecular nanotechnology" as defined earlier. Subsequent discussions addressed public concerns of the possibly negative impact of manufactured nanomaterials on the environment, and the possible effects of such manufactured nanomaterials interacting with biological systems and entering the food chain.[94-98] While discussion of future social and environmental impacts of various nanomaterials was necessarily speculative, the process of having students think about and debate these issues was an important and valuable one, particularly in the context of what has been termed a "preventive approach" to engineering and technological development.[99-102] According to Vanderburg[68,99,100] a "preventive approach" to engineering and technological development is characterized by careful examination of how current and emerging technologies influence human life, society and the biosphere. Conventional approaches to the design and implementation of modern technology essentially are non-preventive, and operate on three fundamental premises, i.e. *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*. However, as Vanderburg[68] convincingly points out, these premises are flawed since "there is no technology without a society, and no society without the biosphere."[68(p.5)] More recently, Devon and van de Poel[103] have argued for a "social ethics paradigm" in which social and ethical concerns are incorporated into the very conceptualization and design of science and engineering research. Interestingly, soon after the conclusion of the Summer 2004 REU program, the Royal Society and the Royal Academy of Engineering in the U.K. released a report entitled *Nanoscience and nanotechnologies: opportunities and uncertainties,*[72] which concluded that "most nanotechnologies pose no new risks, but highlights uncertainties about the potential effects on human health and the environment of manufactured 'nanoparticles' and 'nanotubes' if they are released." Because of their novel physical and chemical properties, the report recommended that "nanoparticles and nanotubes should be treated as new chemicals under U.K. and European legislation, in order to generate appropriate safety tests and clear labelling." The report did not find any justification for imposing a ban on the production of nanoparticles, but as a precautionary measure, recommended that releases to the environment be minimized until the effects are better understood.

As Mnyusiwalla, Daar and Singer[104] caution, 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.[40(p.R9)] This provides a significant impetus for continued efforts to expose future scientists and engineers to these issues.

Probing student and faculty perspectives

An emerging body of literature now exists with regard to public perceptions of nanotechnology research[4, 105-108] and the concomitant development of appropriate social science and public policy.[109,110] However, at present, there is a seeming paucity of published empirical work that has attempted to gauge the perceptions, attitudes and beliefs of nanotechnology researchers concerning social and ethical issues associated with their research. Understanding how prospective and current nanotechnology researchers conceptualize these dimensions of their work is likely to provide valuable insights into the personal and professional motivations that stimulate specific research agenda, and also may be useful in helping to frame appropriate public policy in this area.

With the primary goal of incorporating any interesting findings into future "nanotechnology ethics" seminar offerings, and with the secondary goal of undertaking a pilot investigation that might serve as the "proof-of-concept" basis for future science education research in this area, I initiated a short study during the Summer 2004 REU program that attempted to ascertain student and faculty attitudes to a variety of social and ethical issues currently associated with nanotechnology research. Following a review of the "public perceptions of nanotechnology" Internet survey findings reported by Bainbridge,[105] 22 selected statements were adapted from the report and administered to the 10 students participating in the Summer 2004 REU program (May 2004). Research faculty participating in the Summer 2004 REU program and other faculty at the university whose research programs featured some aspect of nanotechnology also were asked to respond to the survey. The adapted survey was sent to a total of 43 members of faculty *via* electronic mail, and 19 completed surveys were received during June-July 2004. Both students and faculty were given the option to respond anonymously to the survey.[k] The survey statements and student/faculty responses are provided in Table 1 (overleaf).

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k. Some brief comments on the study methodology are appropriate at this juncture. The option of "don't know" deliberately was included as a statement response choice in order to differentiate a truly "neutral" response. A free response section also was included on the survey, in which students and faculty were invited to elaborate on their responses to any particular statement, and/or to critique the wording of any statements. Representative statement items were selected from the "clusters" of suggested survey statements implying a *pro* or a *con* of nanotechnology research. I also deliberately utilized statements suggested by Bainbridge[105] that most closely matched the topics presented and discussions that occurred in the ethics seminars with participating undergraduate students. Since I did not use a pre/post survey design, the intent was not to measure any student attitudinal changes, but rather to obtain a "picture" of what their perspectives were regarding social and ethical issues in nanotechnology research. It is intended that findings from the pilot study described here will form the basis for future work in this area, which may include experimental or quasi-experimental research designs as appropriate.

Table 1: "Attitudes toward nanotechnology" survey
Summer 2004 NANOPAC-REU program (adapted from Bainbridge[105])

Notes:
Numbers below refer to the number of respondents for a particular item.
Where the number of responses for a particular item do not total 19 (for faculty responses) or 10 (for student responses), this indicates one or more responses of "don't know".
Faculty responses are indicated in **bold** type; Student responses are indicated in italics.
SA=strongly agree, A=agree, D=disagree, SD=strongly disagree

Faculty, N=19 (all male) *Students, N=10 (5 male, 5 female)*	SA	A	Neutral	D	SD
1. Human beings will benefit greatly from nanotechnology, which works at the molecular level atom by atom to build new structures, materials and machines.	**14** *3*	**4** *6*	**1** *1*	- -	- -
2. Our most powerful 21st century technologies (i.e. robotics, genetic engineering, nanotechnology) are threatening to make humans an endangered species.	- -	- -	**2** *2*	**4** *4*	**12** *4*
3. As we approach the physical limits of our current technologies, nanotechnology will be important for the continued advancement of our civilization.	**8** *2*	**5** *6*	**4** *1*	**2** *1*	- -
4. Nanotechnology is a natural development of human evolution, so it will enhance our survival.	**3** *2*	**4** *2*	**10** *4*	- *1*	**1** -
5. We should be cautious in the application and use of nanotechnology so that we do not create conditions that might harm our civilization.	**11** *5*	**5** *3*	**2** *1*	- *1*	**1** -
6. It is important for scientists and engineers to assess the social, cultural and ethical implications of their work.	**11** *6*	**8** *4*	- -	- -	- -
7. Nanotechnology –like any other kind of technology- is value neutral and can be used both for benevolent or malevolent purposes.	**2** *1*	**7** *7*	- -	**7** *1*	- -
8. The potential benefits of nanotechnology far outweigh the potential for abuse.	**5** -	**8** *4*	**4** *3*	- -	**1** -
9. The range of possible social and ethical implications of nanotechnology is not fully understood, because it is relatively new.	**5** -	**10** *8*	- *1*	**4** -	- -

10. Practical applications of nanotechnology will enable economic growth with much less of an impact on the environment than today's technologies.	**2** -	**5** *2*	**7** *3*	**3** *2*	- -
11. Nanotechnology has the potential to create unknown environmental dangers.	**1** -	**7** *6*	**6** *2*	**2** -	**1** -
12. Progress in nanotechnology will improve standards of living around the world.	**3** -	**11** *3*	**2** *4*	**1** *1*	- -
13. The biggest risk of nanotechnology is a widening gap between wealthy nations with access to the new technology and nations that do not have access.	**2** -	**5** *2*	**1** *1*	**7** *5*	**1** -
14. It is hard to evaluate nanotechnology until scientific advances actually produce some applications which are studied for long-term social impact.	**4** *2*	**9** *6*	**4** *1*	**2** -	- -
15. It is inevitable that nanotechnology will have military applications.	**11** *3*	**8** *6*	- -	- -	- -
16. Nanotechnology should <u>not</u> be used for military purposes.	**1** *1*	- -	**7** *3*	**6** *5*	**5** -
17. New nanotechnology materials will benefit normal everyday life as well as the business/industry and military sectors.	**7** *3*	**12** *5*	- *2*	- -	- -
18. People's civil liberties will be threatened by the use of nanotechnology in surveillance and information gathering.	**2** -	**4** -	**4** *4*	**5** *4*	**1** -
19. Many currently untreatable diseases and injuries now considered permanent could be cured by advances in nanotechnology.	**5** *1*	**8** *4*	**5** *2*	- -	- -
20. Humans can benefit from having tiny machines installed into their bodies to repair or replace a damaged organ.	**5** *1*	**7** *3*	**4** *1*	- *1*	**1** -
21. Research in areas like nanotechnology is making us less human.	- -	- -	**1** -	**6** *8*	**12** *2*
22. Continued scientific research and discovery at the nanoscale faces some almost insurmountable theoretical problems.	**4** -	**3** *2*	**2** *4*	**7** *3*	**3** -

The small number of respondents (faculty and students) does not permit an exhaustive analysis, however, several patterns of interest present themselves for comment.[1] For the most part, the distribution of student responses was broadly consistent with those of the research faculty. This suggests that the students already were becoming "enculturated" into the attitudinal norms and ways of thinking considered representative of science and engineering researchers.[56] An examination of the combined response distributions indicated several overall trends that may form the basis for further analysis in more detailed studies. Here, I will comment on a few selected statements that are of particular interest to me in terms of how they may influence my design of future "nanotechnology ethics" seminars in the NANOPAC-REU program.

Statements 1 and 2 are those used by Bainbridge[105] in a large-scale Internet survey (3909 respondents) in 2001 to gauge public attitudes to nanotechnology. He reported a statistically significant negative correlation between the two items, i.e. "that there is a powerful tendency for people who *agree* with one of these items to *disagree* with the other".[105(pp.561-563)] The same tendency was supported in the responses of REU students and faculty, although neutral responses also were noted for both statements. Although Statement 1 refers to "nanotechnology" in Feynman's sense of the word, subsequent survey statements do not explicitly specify the sense in which "nanotechnology" is being used, i.e. top-down or bottom-up. Here, I wished to find out if any of the student or faculty respondents would point out whether a distinction between "top-down" and "bottom-up" nanotechnology might make a difference in their responses to the survey statements. With the exception of two faculty members who provided additional narrative data (see below), no other overt distinctions were specified.

In contrast to the exuberance of the speculations offered in Roco and Bainbridge,[32] (in which the convergence of nanotechnology, biotechnology, information technology and cognitive science in the long-term is suggested to have implications for human evolution, including individual and cultural evolution), 53% of faculty respondents and 40% of student respondents indicated a neutral response to Statement 4. It is possible that the noncommittal response (the highest number of "neutral" responses indicated by the research faculty out of all 22 survey statements) may be a function of the respondents' academic backgrounds. With the exception of one faculty member whose expertise was in biomedical research (cell death), all of the other faculty respondents were engineers, physicists, chemists or materials scientists, and only two of the ten students were pursuing undergraduate degrees in bioengineering and biomedical engineering, respectively. (The other eight students were pursuing degrees in chemistry and in electrical, chemical, computer, materials or mechanical engineering, respectively). Without an appreciable background or interest

1. It is hoped that the short study reported in this paper will lead to national and international collaborations between the author and other science and engineering education researchers interested in these issues. The adapted survey used here may be further refined in terms of validity and reliability measures, and administered to a larger group of respondents so that the findings become amenable to detailed statistical analysis.

in evolutionary biology, it is likely that no definitive view could be offered in response to this statement.

While 80% of students strongly agreed or agreed with Statement 7, 37% of faculty indicated agreement *and* disagreement, respectively. Having previously participated in one of the ethics seminars in which we had discussed various theories of technology (including what Feenberg[67] has called an "instrumental theory" of technology), it appears that students identified strongly with this perspective.[m] Based on written comments in the free response section of the survey, it also appears that despite the seemingly definitive responses, several faculty were unclear about what actually was meant by the term "value neutral". This is further discussed below.

Statements 10 and 11 are "*pro* and *con* pair statements" intended to gauge attitudes concerning the effects that nanotechnology and nanomaterials may have on the environment. Here, it is of interest to note that 60% of students agreed that unknown environmental dangers could ensue from continuing nanotechnology research, along with 42% of faculty who strongly agreed or agreed with the same statement. For these pair statements, faculty in particular appeared to be somewhat equally divided in their perspectives, as implied by the range of responses. This suggests that concerns about the environment will be one "social and ethical issue" that will cause protracted debate not only in the public domain, but also between nanotechnology researchers until long-term research studies provide more definitive answers about the interactions of manufactured nanomaterials with the wider environment.

Similarly polarized views on the part of faculty participants also were indicated by the responses to Statements 12 and 13. Seventy-four percent of faculty respondents strongly agreed or agreed that global standards of living would improve as a result of progress in nanotechnology research. However, 37% of faculty also strongly agreed or agreed that there might be a risk of an increasing "economic gap" between countries with access to the technological products and those without.

Statements 15, 16 and 17 all sought to ascertain perspectives concerning potential military applications of nanotechnology research. With the exception of a "don't know" response from one student, the remaining students and all participating faculty indicated their belief that nanotechnology research necessarily would lead to various military applications. Fifty-eight percent of faculty also indicated their strong disagreement or disagreement with the statement that "nanotechnology should <u>not</u> be used for military purposes", with 37% of faculty opting to remain neutral on the matter. As with social and ethical issues related to the environment and global economics, it is to be expected that intense debates regarding military applications of nanotechnology research will ensue in the public domain and also between nanotechnology researchers themselves who care to be involved in these issues.

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m. As Feenberg[67] describes, the instrumental perspective tends to be the most popular and accepted conception of "technology". Those who favor the instrumental perspective argue that various technologies serve only as "tools" designed and utilized by humans for specific purposes. Hence, various technologies in and of themselves are perceived to be "neutral" and therefore free from overt ideological, cultural, social or political biases.

Faculty responses to Statement 22 are especially intriguing. While the statement did not refer to a social/ethical issue *per se*, I included it in the survey out of curiosity about nanotechnology researchers' perspectives regarding the actual science itself. Responses from the 19 participating faculty suggest a lack of professional consensus regarding "how far" continued research at the nanoscale can proceed, with 37% strongly agreeing or agreeing that considerable theoretical problems lie ahead. Written comments in agreement with this statement indicated expected theoretical problems with the prediction of physical properties at the nanoscale and an incipient need to revisit Heisenberg's Uncertainty Principle. However, 53% of participating faculty strongly disagreed or disagreed with this statement. The responses (whether of agreement or disagreement) are indicative of the pioneering and exciting nature of current science and engineering research as we become increasingly more sophisticated in our knowledge about the inter-relationship of energy and matter at the quantum level. However, similar to the current lack of certainty among researchers about the extent to which continued research at the nanoscale may progress, uncertainty also exists in terms of what legitimately might be regarded as "social and ethical issues", and also in terms of how nanotechnology researchers may best address the social and ethical issues associated with these advances. Written comments from student and faculty respondents provided additional data as a complement to the survey responses given above.

Although all student and faculty respondents were encouraged to provide written comments in the free response section of the survey, only one student chose to do so. Here, the narrative sought to clarify (or qualify) the student's responses to the survey statements, i.e. "when I [indicated] neutral, it was generally because I think it depends on the specific case or application". Despite the enthusiastic engagement of students in the "ethics seminars", data from the overall program evaluation findings[56] suggest that considerations of social and ethical issues were not consistently incorporated into the various research project designs. This is borne out by representative student comments below:

> *Every week, we had a seminar on ethics, and sometimes, environmental impact of nanotechnology. However, this was our only exposure to these topics since in the actual research, we didn't talk about the consequences of what we were doing (Summer 2004 NANOPAC-REU student).*

> *The only exposure I get to the ethical, social, and environmental aspects of my research is from the seminars taught by Dr. Sweeney. I do not worry about these issues while working in the lab, nor are they brought up during lab group meetings (Summer 2004 NANOPAC-REU student).*

These statements appear to stand in stark contrast to student and faculty responses to Statement 6 on the survey.

Of the nineteen research faculty who completed the survey, seven provided written comments in the free response section. Short follow-up interviews were scheduled with faculty who agreed to further explain their comments and their responses to the survey statements. The written comments and additional information gathered from the follow-up interviews provide qualitatively rich initial data that may be used to develop theoretical accounts of the various ways in which nanotechnology researchers conceptualize the social and ethical implications of their work, and their role in shaping public policy on these issues. In response to Statement 6 (*It is important for scientists and engineers to assess the social, cultural and ethical implications of their work*) one researcher (chemistry/physics/optics) wrote:

> *I think scientists and engineers should be involved in this process, but not be singularly responsible for the task. This group lacks much of the context needed for these types of judgments. Ultimately, I think policy makers will play the greatest role here. But these must be educated policy makers, who truly understand the potential benefits and risks of the science and technology. The onus then falls upon scientists and engineers to communicate well the value, short-comings, and risks of nanotechnology, and on educators (in its broadest sense) who will create the next generation of policy makers and hopefully a society of informed thinking individuals.*

The same researcher also provided written comments in response to Statement 7 (*Nanotechnology – like any other kind of technology – is value neutral*):

> *I am not sure how value is being used here. I probably don't know how to properly distinguish between "value" and "ethic". My inclination is to think of "value" in terms of "potential", in which case I would say all technologies have "value". Of course it can be applied for good, productive purposes as well as bad and destructive purposes. I have no background in ethics and social policy, but I would like to learn more.*

In terms of whether social and ethical issues associated with nanotechnology research deserved more "special" attention than that given to any other example of technology, two faculty members (physics; chemistry/physics/optics) offered the following:

> *It seems odd to think that nanotechnology will raise social, ethical, or other problems in a way unlike other technologies. We have a long history of what technology does for or to us. This will be just another example.*

> *I think we can prognosticate its potential impact based on other disruptive technologies (automobile, fossil fuels, microelectronics, radio, etc.).*

Another researcher (physics) provided a particularly interesting set of written responses to several of the survey statements. Here, it is important to note how an awareness of the inequities in the global political and economic *status quo* is indicated in the comments. In response to Statement 3 (*As we approach the physical limits of our current technologies, nanotechnology will be important for the continued advancement of our civilization*):

> *Neutral ... which civilization? For the American, it's 'yes'!*

In response to Statement 8 (*The potential benefits of nanotechnology far outweigh the potential for abuse*):

> *Agree ... but this question – as many others here – are too much of a yes or no, black/white comparison. What is the definition of "benefits"? Financial, economical, environmental, superiority (America first), or what? What is "abuse"? There will be "nanothings" good for some and bad for other people.*

Similar comments were provided in response to Statement 13 (*The biggest risk of nanotechnology is a widening gap between wealthy nations with access to the new technology and nations that do not have access*):

> *Strongly agree ... it's a risk arising from big greed and total desperation and disillusion.*

An intriguing response was provided to Statement 20 (*Humans can benefit from having tiny machines installed into their bodies to repair or replace a damaged organ*):

> *Neutral ... applications of nanotechnology however make us more dependent, if I look at the health care and cost of medication now! How can this ever become better ... who pays for extending the life span?*

Comments from two other researchers (nanophotonics; mechanical engineering) expanded on the theme of social and ethical issues associated with specific applications of nanotechnology. Here, explicit distinctions were made between applications of "top-down" and "bottom-up" nanotechnology:

> *I'm interested to hear the results [of your survey]. One remark: it could have been useful to distinguish between nanobiotechnology and other nanotechnologies. For example, it's a different question whether the army should be looking at improving, for example, cameras using nanotechnology, or creating deadly viruses with nanobiotechnology. In terms of ethics I don't feel a nanocomoposite plane wing poses a problem, but optimizing a baby's genome would be. In any case, it's an interesting set of questions.*

> *Nanotechnology is a collection of very wide range of disciplines. As a result, some of the statements can be better addressed if the actual technical application is mentioned. For example, statement number 8 will have different implications for application to the area of energy/power as opposed to the area of mutant gene development.*

Short follow-up interviews were conducted with faculty members who agreed to further clarify their responses to the survey statements. A selection of my interview questions and representative responses are as follows:

> Do you carefully consider the possible risks inherent in the application of your nanotechnology research, and does this influence your decision whether to pursue a particular line of research or not?

> *Not at all, unless it's biological nanoparticles*.

Do you think that your area of nanotechnology research is influenced by certain political, moral, religious, or ethical values? If so, what? If not, why not?

I believe in facts only.

Is there a serious risk that advances in nanotechnology research could exacerbate the economic "divide" or "gap" between countries in certain parts of the world?

I don't think so. However, in any technology revolution there will always be a gap (since money is needed to do research), although in poor nations we can think of other application areas that will be cheaper.

Should nanotechnology researchers be concerned that their work could be used for military purposes? Should these concerns affect or influence a researcher's decision whether to pursue a particular line of research or not?

Nanotechnology research should be done for the benefit of mankind. If it involves making better battlefield armor to protect soldiers, then so be it.

Implications for future design of the NANOPAC-REU ethics seminars

Data from the short study reported here admittedly are limited and should be extrapolated only in a very cautious manner pending the outcomes of similar, but more rigorously designed studies. Nevertheless, based on the available data, several implications suggest themselves for how I might modify the structure of future "nanotechnology ethics" seminars. Other science and engineering education researchers interested in "nanotechnology ethics" are invited to provide relevant comments, critiques and suggestions.

Generally, participating REU students indicated a high level of interest in the topics raised and discussed in the seminars, which, it appears, had prompted them to think more widely about the social, ethical and environmental implications of nanotechnology research than they otherwise might have. As the instructor of the seminars, I find this to be a modest but important outcome:

The group meetings helped me to understand several ethical and environmental issues that I may not have thought about before, such as equity when something significant is developed. Sometimes I get focused on either the goal of the project and what it can do, or the larger, more dramatic scientific issues, when other ethical issues can be just as important (REU 2002 student).

Our seminars in ethics brought about thought-provoking discussions about science and technology in general and allowed me to think about the potential consequences of my research (REU 2003 student).

Assessing and addressing ethical, legal, economic, social and political impacts of the research design ... this area had a huge impact on my research *experience. Dr. Sweeney's seminars on ethics were extremely rewarding. I have never had the opportunity to take an ethics course, in addition to applying it to the particular field of study I am working on. I didn't quite understand how important ethical considerations for major new research areas really are, and being a part of Dr. Sweeney's class taught me that importance. Not only that, but ethics is so incredibly interesting for me (REU 2004 student).*

However, despite these comments, there is a need for the "social and ethical issues" component of the NANOPAC-REU program to be restructured. Even though participating faculty and students agreed that such issues were of particular interest to the science/engineering research community (and in some cases, expressed the necessity for such issues to be considered), there is scant evidence (as mentioned earlier) that any such considerations were substantively incorporated into the design and subsequent performance of the respective research projects. An increasing number of researchers in engineering ethics and engineering education now advocate for social and ethical concerns to be treated not merely as an "add-on" to the main business of research, but as an integral part of the research process from conceptualization to design to execution to application development.[99,101,103,104,111-113] This will necessitate closer professional collaborations between science and engineering laboratory researchers, science and engineering education researchers, and researchers with expertise in the philosophy and ethical aspects of science and engineering research. Similar to the curricular design described by van der Poel, Zandvoort and Brumsen,[112] for future offerings of the NANOPAC-REU program, I will consider the inclusion of a short written "case study" essay assignment which asks students to explicitly discuss potential social, ethical and environmental concerns which may arise from full development and application of their respective research projects. It also will be useful to solicit the direct involvement of interested research faculty in the ethics seminars. Here, faculty actively engaged in some aspect of nanotechnology research would be asked to discuss explicitly what they perceive to be the social and ethical issues that may derive from their research, either at the level of the basic science, or in terms of future technological development and application. Given the range of faculty perspectives to various issues indicated in the survey, it will be instructive for students (i.e. prospective researchers) to learn "first hand" how current researchers conceptualize these issues, followed by my examination and analysis of the various perspectives in the manner I have described above.

As I reflect on the survey findings and review feedback (both formal and informal) regarding the ethics seminars that I have received from students since the beginning of the NANOPAC-REU program in 2002, the question arises of who is "best suited" or "best qualified" to meaningfully engage students in critical examinations of social and ethical issues deriving from nanoscale science and engineering research. In their examination of the main strategies commonly used to integrate ethics into the engineering curriculum (i.e. the "stand-alone course"; the approach "mandating ethics content in every engineering course"; and "outsourcing ethics instruction to an external expert"), Lincourt and Johnson[114] argue that all three strategies leave much to be desired. They suggest that a more effective approach is to utilize a "special modular option", where, although some assistance is provided by a professional ethicist, the primary person responsible for these offerings "is a high-profile engineer who shares an ethics dilemma encountered in professional practice".[114(p.353)] To some extent, I agree with this recommendation, as suggested above in terms of future modifications that might be made to the design of the NANOPAC-REU program. A rather scathing critique is given by Lincourt and Johnson[114] to the practice of "relinquishing ethics to outsiders", which, they maintain, requires the least effort and generates the smallest benefit.[114(p.355)] While I do not agree with the idea of "relinquishing" or "abandoning" ethical matters pertaining to science and engineering research to those having very little or no understanding of the relevant underlying scientific and engineering principles,[n] the argument may be made that ethics courses (whatever the format) from "outside" science and engineering are likely to offer an advantage of incorporating wider perspectives and other important considerations than typically would be raised by scientists and engineers alone. This appears to be particularly applicable to social and ethical issues associated with nanotechnology research, and as Khushf[115] eloquently states, "ethical issues in nano-science reflect the character of the new science itself. No longer can such issues be dealt with in an isolated way by "ethicists" or by scientists alone. The issues are now too complex, and they require the full range of skills of those in the sciences and the humanities."[115(p.147)] As science and engineering education research continues to develop in this area, we can expect to learn more about the pedagogical approaches that appear to be useful and effective for teaching about "nanotechnology ethics".

SUGGESTIONS FOR FURTHER INQUIRY AND CONCLUDING COMMENTS

An increasing number of thought-provoking and informative commentaries regarding "nanotechnology ethics" continue to be published by a variety of social science researchers (including ethicists, science, engineering and environmental educators, philosophers of science, legal analysts, etc.). However, to my knowledge, the short study reported here represents one of the first attempts to ascertain the perspectives of prospective and practicing nanotechnology researchers themselves concerning the wide-ranging social and ethical implications of their research.[o] I suggest that it is necessary to develop a systematic account of both sets of perspectives, which then can

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n. Being a *science* education professor with a formal academic background in chemistry (and being able to discuss the fundamental chemical and physical principles underlying the students' nanotechnology research projects) very likely conferred a certain amount of "legitimacy" on my efforts to subsequently engage the students in thinking about and discussing social and ethical issues associated with nanotechnology research.

o. During the time in which this manuscript was undergoing review for publication consideration (July-November, 2005), Rosalyn Berne's[116] book-length study, *Nanotalk*, was published. Readers are referred to the book for an exceptionally in-depth and cogent analysis of several issues discussed here.

lead to an analysis of areas of common concern, and an elucidation of the areas in which marked differences of perspective may exist. To my mind, only in this way can any meaningful, sustained and productive dialogue ensue between those actively engaged in nanoscale science and engineering research, and those (like myself) whose professional priorities focus on social science research and public education. At time of writing, my colleagues and I at the University of Central Florida now have received funding for a second 3-year cycle of the NANOPAC-REU program (2005-2007), and I am interested in building on what has been learned during the first 3 years not only to improve my "nanotechnology ethics" seminar offerings in the program, but also to stimulate dialogue and corresponding research efforts with others (from the social sciences and from the various areas of nanotechnology research) who are interested in these issues.

In addition to what currently is known regarding the attitudes of the general public toward nanotechnology research, it also will be necessary to investigate the perceptions of those responsible for influencing and shaping various national public policies such as those in the areas of economics, environmental stewardship, healthcare and education. The ambivalence of faculty responses to several of the survey statements used in this study may be reflective of attitudes in the wider nanotechnology research community, but without further inquiry we will not be able to determine this in a more definitive manner. Such efforts will assume increasing importance if indeed the goal of "responsible development of nanotechnology research" is to be achieved, taking into as full an account as possible the many social and ethical issues with which we now are faced as a global society. Recently, Berne[24] has cautioned that "the development of nanotechnology is moving very quickly, and without any clear public guidance or leadership as to the moral tenor of its purposes, directions and outcomes; where nanotechnology is leading and what impact it might have on humanity is anyone's guess,"[24(p.631)] Based on my interactions to date with nanotechnology researchers both at my institution and at several others, it appears that "the impact nanotechnology might have on humanity" largely is being thought of in terms of novel sources of energy and energy storage, human health and the environment, advances in information storage technology, and potential military applications. Effects on global business trends, financial investing, intellectual property and patenting also bespeak future impacts at various levels.[117-120] What appears to be missing at the present time is a clearly articulated prognosis of the potential global social benefits and harms that may develop from further scientific and technological advances in all of these areas.

Consideration of social and ethical issues associated with nanotechnology research also is likely to generate several implications for general scientific literacy and public science education policy. According to Roco,[34] "education and training [in scientific concepts at the nanoscale] 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."[34(p.1248)] Given the extent to which these new technologies are expected to impact all aspects of human experience, public scientific literacy regarding nanotechnology becomes an issue of considerable importance. Here, the onus falls on science educators at the K-12 and university levels to become knowledgeable about nanotechnology, and to share their pedagogical expertise with nanotechnology researchers. It is to be expected that the various professional science teaching and research organizations worldwide, will, in due time, develop nanotechnology-specific instructional guidelines and recommendations that complement the "social and ethical issues in science" standards already present in documents such as the U.S. *National Science Education Standards* (e.g. "Science in Personal and Social Perspectives Standards" & "History and Nature of Science Standards"; see www.nap.edu/readingroom/books/nses), the *American Association for the Advancement of Science's Project 2061 Benchmarks for Scientific Literacy* (e.g. "Nature of Science" and "Nature of Technology"; see www.project2061.org), and the *British National Curriculum* (e.g. "Ideas and Evidence in Science"; see www.nc.uk.net).

Within a relatively short period of time, much has been accomplished in the rapidly developing fields of nanotechnology research, with new discoveries and advances now being reported worldwide on an almost daily basis. However, without adequate forethought and analysis of the ways in which these advances will materially affect our social interactions, our habitable environment and relationships of power, then as a global society we will be at a considerable disadvantage when faced with fundamental social and ethical issues that advances in nanotechnology research are likely to engender.

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