Nanotechnology and Society: A discussion-based undergraduate course

Charles Tahan[a)]
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Ricky Leung
Department of Sociology, University of Wisconsin, Madison, Wisconsin 53706

G. M. Zenner
Materials Research Science and Engineering Center, University of Wisconsin, Madison, Wisconsin 53706

K. D. Ellison
Graduate School, University of Wisconsin, Madison, Wisconsin 53706

W. C. Crone
Department of Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706

Clark A. Miller
LaFollette School of Public Affairs, University of Wisconsin, Madison, Wisconsin 53706

(Received 26 July 2005; accepted 27 January 2006)

Nanotechnology has emerged as a broad, exciting, yet ill-defined field of scientific research and technological innovation. There are important questions about the technology's potential economic, social, and environmental implications. We discuss an undergraduate course on nanoscience and nanotechnology for students from a wide range of disciplines, including the natural and social sciences, the humanities, and engineering. The course explores these questions and the broader place of technology in contemporary societies. The course is built around active learning methods and seeks to develop the students' critical thinking skills, written and verbal communication abilities, and general knowledge of nanoscience and nanoengineering concepts. Continuous assessment was used to gain information about the effectiveness of class discussions and enhancement of student understanding of the interaction between nanotechnology and society.
[DOI: 10.1119/1.2178845]

I. INTRODUCTION

Nanotechnology is cool. This truth has great allure to students and educators both. As public attention to nanoscale science and engineering spotlights research and the potential of new discoveries, students are pulled toward careers in science, engineering, and related social sciences or businesses. Educators not only have a new field of endeavor and questions to explore, but also another hook to gain the attention and interest of students. Nanoscale science and engineering raises many important questions, especially at the intersection of technology and society. Government funding of the field, which includes funds specifically earmarked for environmental and societal impact studies,[1,2] shows that policy officials are focused on addressing these societal concerns. The ability to create nanoscale materials and devices will generate new ways for people to understand and exploit nature. But who will have access to these new capabilities? How will they be applied? By whom? What are the consequences for our society?

It is incumbent on science and engineering educators to partner with their counterparts in the social sciences and public policy to bring the discussion about the connections between technology and society to undergraduate students. Before this course, a curricular gap existed in nanoscale science and engineering education at the University of Wisconsin-Madison (UW). Nanotechnology education has primarily focused on the field's technical aspects, with little emphasis on issues such as the social and ethical implications of design choices, public attitudes toward new technologies, and nanotechnology policy.

A course on nanotechnology and its societal implications can serve multiple purposes. Recruitment, education, introduction to nanoscale science and engineering, and science and technology studies (STS) all fall in its scope. STS itself is an umbrella term for a number of related topics including the sociology of science knowledge, philosophy of science, and history of science and technology. Here we describe a nontechnical course for undergraduates that introduces a broad audience to nanoscale science and engineering and STS. The course is open to all majors and satisfies a humanities requirement for undergraduates. Although designated as a 200-level class (freshmen or sophomores), the course was open to all students. The course is discussion-based, requires active student involvement, and focuses on readings, group discussion sessions, role-playing exercises, essay assignments and exams, and a semester-long research project with a final presentation.

The course, Nanotechnology and Society, was offered in two sections in the spring of 2005. Two sections of a STS course, Where Science Meets Society, were designed and led by a graduate student specifically trained in nanoscale science and engineering and STS in the previous semester. In prior versions of the latter course STS topics were covered in a more general context of many technologies, without including learning of specific science concepts or facts. The course is regularly taught as a first-year seminar and satisfies either a humanities or social sciences requirement within the university's core liberal arts curriculum. It is well known by first-year advisors in the College of Letters and Science and the College of Engineering and has proven successful in drawing students from humanities, science, and engineering.

This year, two sections were separated and designated for the new course on Nanotechnology and Society. This paper discusses the section[3] taught by co-author Tahan, a physics graduate student; the other section was taught by co-author Leung, a sociology graduate student. Both courses were based on a similar core curriculum developed in the prior semester.[4]

II. PREPARATION

To develop an effective undergraduate course in nanotechnology and society, we first needed to educate the educators. To this end, a seminar was created for advanced graduate students in the sciences, engineering, humanities, and social sciences to explore questions about the connections between nanotechnology and societal issues and to reflect on the broader place of technology in modern societies. The instructors for this seminar (co-authors Zenner, Ellison, Crone, and Miller) came from backgrounds in engineering, public policy, and the humanities. In addition, a partnership was initiated through a National Science Foundation funded Nanotechnology Undergraduate Education grant between the Materials Research Science and Engineering Center and the Robert and Jean Holtz Center for Science and Technology Studies, a newly established center for research and teaching in the history, sociology, and philosophy of science, technology, and medicine at UW.

The seminar was offered to graduate students for either one or three credits. Students who chose the one-credit option were expected to attend the seminar's first hour, read and discuss the class materials, and write a one-page response essay each week. This part of the seminar, attended by ten graduate students and post-doctoral associates in the Fall 2004 semester, focused on theories and approaches to understanding the social dimensions of technology applied to the case study of nanotechnology. More detailed course information is provided in Refs. 4 and 5.

The three credit option had an additional emphasis on the development of teaching skills and the creation of a teaching portfolio. Students who chose this option attended a second hour of the seminar and developed an annotated syllabus for an undergraduate seminar in nanotechnology and society. This portion of the course was designed for future educators who wished to teach nanotechnology and society topics, either as a stand-alone course or as part of another course. These students also led the discussion in the first hour on a rotating basis, giving them an opportunity to test various active learning techniques such as think-pair-share, jigsaw (where the class is divided in parts to solve a problem), town-meeting formats, group discussion, and blackboard exercises. This second part of the seminar introduced approaches, materials, and skills for teaching undergraduates how to think critically about the social aspects of technology. Four graduate students completed the three credit course, including the two who taught their own courses in the spring. One of these courses is described here.

III. GOALS AND COURSE CONTENT

STS 201, Nanotechnology and Society, set broad goals in both its scope and content. As stated in the syllabus, the objectives of this course include the following:

(1) Introduce the broad field of nanotechnology and the basic science and technology.
(2) Consider the societal implications of nanotechnology in the context of social, scientific, historical, political, environmental, philosophical, ethical, and cultural ideas from other fields and prior work.
(3) Develop questioning, thinking, idea producing, and communication skills, both written and verbal.

Because STS 201 was primarily a humanities course, the focus was on understanding the implications of technology and its interactions with society, specifically applied to nanoscale science and engineering. From a deeper curriculum perspective, the goals include the following.

(1) Introduce the various social theories of technology, such as technological determinism and the social construction of technology.
(2) Explore the wider social, historical, and cultural contexts in which nanoscale science and engineering are embedded.
(3) Examine the technical and social elements of nanotechnological systems.
(4) Provide skills and resources for learning about the technological infrastructures of modern societies and the potential impacts of developments in nanotechnology.
(5) Investigate why people sometimes fear new technologies, including studies of technological utopias and dystopias, accidents, risk, and concerns about loss of control.

An obvious question is how much science was included. Students were required to learn some of the basic science of the nanotechnologies discussed in class. We illustrate the level by the example of the nanotechnology of nanocrystals or quantum dots. The students were expected to learn some primitive semiconductor physics to understand why nanoscale semiconductor crystals exhibit new properties, such as changes in color emission at certain size thresholds. The notion of a band gap between core (valence) electron levels and free (conduction) levels was introduced with a discussion of light (photon) excitation. Students were expected to learn how the energy gap between the electron levels changes with decreasing size and the reason (quantum confinement effects). This understanding was then compared and applied to the application of quantum dots for medical contrast imaging. Lectures in addition to books for a lay audience, for example, Refs. 6–11, provided the main teaching materials.

The class outline given in Table I is mostly chronological except that the nanoscience subtopics were distributed throughout the semester instead of at a single time. We began reading general introductory articles on nanotechnology such as found in popular science magazines, think-tank and corporate reports, and then began looking at the STS topics one-by-one, intermixing STS topics with nanoscale science and engineering. In the last few weeks the students reported on their research on a specific topic in nanoscale science and engineering.

The STS readings were introductory in nature (such as in Refs. 12–23) and assumed an audience not familiar with the more complex analytical techniques and terms that are used in higher level sociology or history of science courses. The readings for this section are available online.[3] The overall curriculum consisted of components that introduced a concept in STS and then used STS as a means to apply or interpret the concept.

Table I. Course outline. The course materials can be found online (Ref. 3).

(1) Introduction to Nanotechnology and Society (classes 1–3, essay 1). How is nanotechnology defined?

(2) Nanoscience/technology (classes 4, 5, 10, 12, 14, 37–44).
(a) Policy reports and reviews.
(b) Topics: New nanoscale effects; quantum vs classical; Nano-manufacturing; quantum dots and nanoparticles; carbon; medical applications.
(c) Student research projects and presentations.

(3) Nanotech in Culture (classes 6, 8, 9, 22, 24, 46).
(a) What real nanoproducts are on the market now and what's nanohyped?
(b) How does science fiction bring science/technology to the public? See Refs. 24–26.
(c) How has nano seeped into the media?

(4) Revolutions and the History of Science and Technology (classes 31, 46, essay 3). Is nanotech a new industrial revolution?

(5) Technology and Society (classes 7, 9, 11, 13, 15, 16, 24, 32, 46, essay 2).
(a) Do technological innovations necessarily contribute to progress?
(b) How does technology affect the way we live?
(c) How do the users shape the development of technology?
(d) Is technology political?

(6) How Government Drives Technology (classes 23, 25, 46, essay 4).
(a) How much money is being invested in nanotechnology and science?
(b) What agencies handle nanotech funding?
(c) How does the military's needs shape our world?

(7) Weighing the Risks (classes 33, 34, 35, 36, 46, essay 4).
(a) How does society decide what kinds of risks are acceptable given the possible consequences of pursuing a certain technology or science?
(b) Is nanoscale science and engineering more dangerous than micro?
(c) What is a normal accident?

(8) Thinking About the Future (classes 30, 45, 47).
(a) What do the minds of today (or at least those who get media attention) think about nanotech? (See for example, Refs. 27 and 28.)
(b) More Science Fiction.
(c) Reflections. What have we learned?

Table II. Essay assignments (abbreviated).

(1) You are interviewing for a job at McKinsey, a prestigious consulting firm. During your interview you mention that you have experience thinking about the societal implications of technology, specifically nanotechnology. The interviewer asks you to go home and write a two to three page executive summary defining nanotechnology (which she, a nonscientist, can understand) and suggesting specific areas where McKinsey may be able to do in the future. You must really impress her to get the job.

(2) Does nanotechnology have politics? Make your case, for or against, using the articles we have talked about in class (see, for example, Ref. 12).

(3) Is the field of nanotechnology a revolution or just evolution?

(4) Write a brief testimony to be presented to the congressional subcommittee reviewing the National Nanotechnology Initiatives and address the following questions. Should the government continue funding of research in nanotechnology? In what specific areas? How? Should the public be brought into the nanotech development process? How? You will represent a specific political group, for example, the military or AAAS.

IV. REQUIREMENTS AND OUTPUT

Because the course was primarily discussion based, class participation (including homework) was highly valued and vital to exploring the issues fully. It counted for 25% of the grade, including the expectation that students participate or lead group discussions, present before the class, and participate in debates, mock hearings, or other cooperative activities. Reading was assigned for nearly every class, but homework was occasional and included small writing or research assignments to be shared with the class. An example was an assignment for which the students chose from a list of professors at the university doing nanoscale science and engineering research and reported to the class on the interests of a particular research group. Another assignment was to find a nanoscale science and engineering product in the news, learn about it, and teach what they learned to the class.

To a large extent the course was about connecting disparate questions, concepts, facts, and ideas, and then raising new questions. Writing is a vital process in this approach to thinking because it is a formal way of integrating ideas and communicating. There were four, 2–3 page, double-spaced response or op-ed type essays for each of the main topics (see Table II). The four graded essays counted for a total of 20% of the grade.

Two formal exams counted for another 25% of the grade. The remaining 30% of the course requirements was assessed from individual research projects and class presentations. A list of topics was developed by the instructor, and each student selected one and become the class "expert" on it. These topics provided a means to explore in more depth some of the subfields of nanoscale science and engineering and allowed the students to teach each other instead of sitting through lectures by the instructor. The goal was to produce a pamphlet on key nanotechnologies circa 2005 that may have value to future iterations of the class and to the public. It also provided an opportunity for more advanced students to contribute their particular expertise that might be outside the realm of the instructor's specialty. Approximately two-thirds of each roughly five double-spaced page report covered the science of the selected topic with the last one-third on the societal implications. Each student also gave a 20 minute PowerPoint or blackboard presentation. Examples of the nanotopics include nanonuclear batteries, nanotechnology and cancer, nanofiltration, and nanotechnology and agriculture. The student reports and presentations are also available.[3]

V. ASSESSMENT

In addition to the traditional evaluation of student work discussed in Sec. IV, several surveys were given during the semester to gauge the students' perceptions of the course and to provide feedback on further improvements.

A brief preassessment was given on the second day of class and two more detailed assessments were given in the last week of class, in addition to several unofficial feedback surveys during the semester. The assessments and surveys show that the students found the course valuable and that many of the goals in the syllabus were met. A typical student comment was "I really enjoyed the class. Not only did I learn about what advances have been achieved (or will be soon), but also the social implications towards using/creating technology."

The preassessment attempted to gauge the comfort and knowledge levels of the topics to be studied in the course as

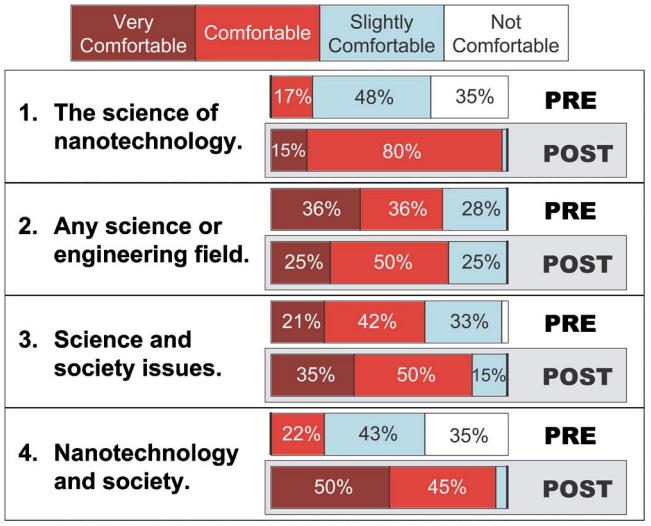

Fig. 1. Pre- and post-assessment answers to the question: "Please rate your comfort level with the following topics."

well as of nanoscale science and engineering in general. Figure 1 shows the results of the comfort level assessment before and after the bulk of the course. Of note is the general increase in comfort level for all topics and the improvement in the area of nanotechnology and society. By the end of the course 95% of the class claimed to be "comfortable" or "very comfortable" with the subject, a tremendous improvement. In addition, the preassessment asked the students to define nanotechnology and list several nanotechnologies that they knew, as well as whether and where they had heard the term. About a quarter of the class said that this course was the first time they had heard the term. The others cited news, TV, or science fiction as their source of introduction. Initially, most students described nanotechnology as "tiny," "microscopic," or "advanced." The most common answers were variations on "the study of small particles or very small technology" or circular definitions such as the "study/design/manufacturing of products/objects at the nanoscale." Only one student cited 1×10^{-9} meters as a benchmark. Before the course students cited "advanced/really-fast computers" as the most common example for nanotechnology, followed by "medical/medicine," and "stain free pants."

The final exams and post-assessment asked these same questions again plus more in-depth questions about the students' knowledge of nanoscale science and engineering. When asked to define nanotechnology, almost all the students were able to give a working definition of nanoscale science and engineering on par with or surpassing the definitions found elsewhere. The students also could cite examples of new phenomena that occur at the nanoscale including increased reactivity, quantum confinement effects, and biological coincidences (such as the ability of nanoparticles to cross the blood-brain barrier), as well as more specific examples. All the students were able to give three examples of specific nanotechnologies. Moreover, the students were able to formulate three meaningful questions about the societal implications of nanoscale science and engineering, a question on the preassessment that was left mostly blank.

The post-assessment included additional questions to judge the impact of the course on the students. The students were asked to summarize the class in a sentence or two; the following comment is representative. "This class gave me a good overview of the science of nanotech and its societal implications. I now feel much better about current trends in the field."

To fully interpret the post-assessment results, it is useful to revisit the students' backgrounds and motivations. Many of the students (14) took the class to fulfill a humanities requirement with about one-half also citing a general interest in nanotechnology. Out of 22 total students, roughly two-thirds did not come from a humanities background but instead came from the engineering and natural sciences, business, and related fields. Out of five women and 17 men, there were four freshman, 10 sophomores, three juniors, and five seniors. The largest contingent from any one major was from biochemistry (4) followed by computer science (3).

Fourteen students would take the course again even if it did not fulfill a requirement, although one-quarter would not. Nearly all (17 yes, 3 maybes) would recommend the course to another student. All said their knowledge of the science of nanoscale science and engineering improved because of this course. One student commented: "I knew very little about nanotechnology and I was surprised by how much there is." Nearly all (17) said the course made them very or extremely well prepared to explain what nanoscale science and engineering is. For example, one comment stated that the course "provides a basic, layman's definition as well as an in-depth definition." Nearly all (18) considered "nanotechnology and society a valuable field" of intellectual pursuit, which was somewhat surprising to us considering the newness and ambiguity of the field when we started.

Before the course, most students were planning on pursuing a career in science and engineering (3 were not, 2 maybe), and none were considering one in nanotechnology. Students were largely not encouraged to change to a more nanorelated career (8 maybe, 10 no), but the course encouraged them to be aware of opportunities and relations to nanoscale science and engineering in their planned field (15 yes). The course did not encourage the students to pursue a career in STS or policy (5 maybe, 16 no). Three-quarters of the class said that their perspective on science, technology, and societal implications changed as a result of the class. A typical student comment was that "Before the course, I thought any/all technological improvements were good. Now I understand more of the social issues of new technology."

Most of the students thought the class was sufficiently challenging, although a few expected more and most thought the course could not or only might be improved significantly. About one-quarter of the students would have liked to see more science, about one-quarter thought there was too much, and 50% thought it was a good mix. The students preferred in-class activities, debates, town-hall meetings, and generally doing the work themselves over traditional lectures. The research project presentations were universally thought to be a good idea, but the students would have preferred more specificity and direction from the instructor.

Finally, the essay assignments provided a means to apply and test the application of higher order analytical skills and concepts to present day issues in nanotechnology and society. Although assessment cannot be quantitative in this regard, we found that the students did reasonably well (with some variation in skill level) in thinking creatively and knowledgeably on the issues in question. Not only did they show a growing understanding of how nanotechnology will

affect society (with past technologies as test cases), but how society can determine the evolution and application of technology (see Table II).

A rewarding message from the post-assessment and in-class surveys was that the students overwhelmingly preferred discussion/group-oriented classes over lecture-oriented classes. "Some of the more science based aspects are taught better in lecture format. This was done for the main part. But implications on society is better in discussion format." Another good point was "nanotech is changing so fast, it'd be bad to try and follow a pre-established lecture schedule."

VI. DISCUSSION AND REFLECTION

A social science course that focuses on technology creates unique challenges and new opportunities for education. With over one-half of the class composed of science or engineering majors, there was a bias against the more open-ended, subjective questions that can be posed in science and technology studies. Many students expected a class about nanotechnology.

Clarity is the first step in good student engagement. The philosophy and content of the course must be clearly and repeatedly explained, focusing on why the subject is worthwhile and what will be gained from a significant time investment. The instructor's (CT) technical background helped somewhat in that it gave credibility and a starting point for a new direction of intellectual pursuit. In the end though, personal attention—learning the students' names, majors, career plans, interests—is necessary to enlist the class in learning, especially in the context of group work, class participation, and active learning activities. Not surprisingly, this attention requires much effort on the instructor's part. It is also tremendously rewarding.

Teaching the course required a lot of leadership. We pushed and pulled in different directions as the course navigated through various paces and types of content. We bounced back and forth between STS and nanoscale science and engineering to keep student interest and integrate concepts and theories. Because the course was offered for the first time, extra preparation was needed for each class. The course schedule was also quite fluid as the order and depth of the course material was continually calibrated to match the students' learning pace and the instructors' growing experience.

We had thought the students would be mostly in their first year. Instead, we attracted a much more diverse and older student body. Older students with science and engineering majors tend to be more resistant to active learning techniques and class participation. They are also more competent overall, be it in writing, reading, or analytical comprehension abilities, which can lead to boredom in mixed skill-level environments. We made this overqualification into an opportunity. The research projects and essay assignments provided a good way to challenge the students while keeping everyone engaged at their ability level. The nanoresearch projects became continuing educational tools for both the researcher and the rest of the class in research and communication techniques as well as general knowledge.

So how much work did it take? For the students, a balance had to be maintained between university requirements and their expectation and commitment level. The class decided collectively to meet as groups in-class but have individual homework and assignments outside of class. For important concepts or theories in STS, the class settled into a routine of working in groups on work sheets or quizzes provided by the instructor, then as a class reviewing their work. The nanoscience discussions tended to be more whole class oriented with individual students contributing their research or perspective. After the learning goals were set by the instructor, the class preferred to work in small groups. The amount of work required on the students' part was similar to other courses at the university.

The instructor had more extensive duties. In addition to preparing for a course with no standard text for the first time, the research projects required special attention. The students learned more about nanoscale science and engineering through the projects and applied their newfound societal analytical toolset to explore the implications of their nanotopic. The instructor's philosophy was to model the progress and requirements of the project on a real-world research group, where the students would need to meet milestones and share their progress with the rest of the class at group meetings. The formal class presentation was a step in this process of producing a readable report. The implementation of this approach was good but not perfect. Some of the students would have benefited from more hand-holding and specification. Despite the instructor's not limitless time, the assessments showed that the experience was found to be valuable by almost all of the students. In summary, realistic time constraints were not a barrier to preparing and teaching an effective and interesting course from our perspective.

Scientists and technologists, as well as science students, consider the societal ramifications of technology all the time. Well, at least they should. But thinking critically about such issues in a course involving science and technology studies, history of science, and public policy professionals is generally a new and very worthwhile experience. An exciting new field of study like nanotechnology can provide the basis for learning about the issues of technological change alongside technological developments in real time.

ACKNOWLEDGMENTS

The authors are grateful to the National Science Foundation through the Materials Research Science and Engineering Center on Nanostructured Materials and Interfaces (DMR-0079983) and through the Nanotechnology Undergraduate Education (NUE) grant, *An Integrated Approach to Teaching Nanotechnology and Society* (DMR-0407075). Both programs are at the University of Wisconsin-Madison. The authors thank the EPD 690 students for their help in thinking about the complex issues surrounding nanotechnology and society. In particular, the authors thank Anne Bentley and Adam Creuziger for participating in the second portion of the course and creating syllabi and other course materials. One of the authors (C.T.) would like to thank Robert Joynt for allowing him to develop and teach this course while pursuing his Ph.D. in physics.

[a]Electronic mail: charlie@tahan.com

[1]M. C. Roco, "Broader societal implications of nanotechnology," J. Nanopart. Res. **5**, 181–189 (2003).

[2]M. C. Roco, "The U.S. national nanotechnology initiative after 3 years," J. Nanopart. Res. **6**, 1–10 (2003).

[3]C. Tahan, Nanotechnology and Society, ⟨www.tahan.com/charlie/nanosociety/course201/⟩

[4]W. C. Crone, G. M. Zenner, C. A. Miller, K. D. Ellison, and A. K. Bentley, "Addressing the societal context of nanotechnology in the classroom," *Proceedings of the 2005 SEM Annual Conference and Exposition on Experimental and Applied Mechanics* (SEM, Portland, OR, 2005), Vol. 68, pp. 1–4.
[5]UW-Madison, ⟨www.mrsec.wisc.edu/Edetc/courses/⟩
[6]*Understanding Nanotechnology* (Scientific American Press, New York, 2004).
[7]I. Amato, *Nanotechnology: Shaping the World Atom by Atom* (National Science and Technology Council, Washington, DC, 2000).
[8]Nanotechnology—Small matter, many unknowns, ⟨www.swissre.com/⟩
[9]R. Waser, *Nanoelectronics and Information Technology* (Wiley-VCH, New York, 2003).
[10]D. Talbot, "Super soldiers," MIT Tech. Review **105** (8), 44–50 (2002).
[11]Institute for Soldier Nanotechnologies promotional video, ⟨web.mit.edu/isn/aboutisn/isnvideo.html⟩
[12]L. Winner, *The Whale and the Reactor* (University of Chicago Press, Chicago, IL, 1986).
[13]Langdon Winner, "Testimony to the Committee on Science of the U.S. House of Representatives on the societal implications of nanotechnology," April 9, 2003). Also available through Ref. 3.
[14]D. Mackenzie and J. Wajcman, *The Social Shaping of Technology* (Open University Press, 1999).
[15]G. Cross and R. Szostak, *Technology and American Society: A History* (Prentice-Hall, Englewood Cliffs, NJ, 1995).
[16]H. Collins and T. Pinch, *The Golem: What You Should Know About Science* (Cambridge U. P., Cambridge, 1998).
[17]H. Collins and T. Pinch, *The Golem at Large: What You Should Know About Technology* (Cambridge U. P., Cambridge, 1998).
[18]J. Brockman, *The Next Fifty Years* (Vintage Books, New York, 2002).
[19]S. Jasanoff, G. E. Markle, J. C. Petersen, and T. Pinch, *Handbook of Science and Technology Studies* (Sage Publications, New York, 1995).
[20]A. H. Teich, *Technology and the Future* (Wadsworth, New York, 2002).
[21]M. R. Smith, *Military Enterprise and Technological Change: Perspectives on the American Experience* (MIT, Cambridge, MA, 1987).
[22]C. Perrow, *Normal Accidents* (Princeton U. P., Princeton, NJ, 1999).
[23]A. Irwin, *Misunderstanding Science: The Public Reconstruction of Science and Technology* (Cambridge U. P., Cambridge, 2004).
[24]M. Flynn, "Soul of the city," Analog #2, L100–L105 (1989).
[25]"The new breed" (TV episode), The (New) Outer Limits, Season 1, MGM, 2001. A nanotechnology professor creates a strain of nanobots that can cure anything. His sick brother-in-law (a sociologist) injects himself with the nanobots which "improve" him, eventually leading to a horrific death.
[26]"Learning curve" (TV episode), Stargate SG1, Season 3, MGM, 2003. A society is discovered that acquires knowledge by implanting a few of their children with nanites at birth, before the brain has fully developed. The nanites act as additional synapses, allowing the children to learn vast amounts of knowledge very quickly. When the child has reached 12 years of age, his or her nanites are harvested and one is given to every adult citizen, sharing their knowledge.
[27]K. E. Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (Anchor Books, New York, 1987).
[28]D. Mulhall, *Our Molecular Future* (Prometheus Books, New York, 2002).

THE INTERNATIONAL FELLOWSHIP

In his perfect world, the scientist serves only his discipline and knows no nation. Discovery works best if thought is unfettered. Political issues, or consequences, are unimportant. While soldiers and politicians increasingly looked to the laboratories to provide more efficient instruments of death, the scientists themselves desperately defended the sanctity of their ivory tower. They maintained a community of their own which had no national boundaries and lived according to its own system of law and morality. For those who had to endure the repressive regimes of Central Europe, the liberal laboratory provided attractive refuge. The Hungarian Edward Teller felt that science ''offered a possibility of escaping this doomed society. For Einstein, ''science . . . was an international fellowship and a culture that could be packed up and taken with one anywhere in the world.''

Gerard J. DeGroot, *The Bomb: A life* (Harvard, 2005), p. 11.