The United States Congress is currently refining the details of a Nanotechnology Research and Development Act that allocates $2.4 billion in funding over three years for basic investigations of nanotechnology by non-Defense Department federal agencies [1]. This investment is in addition to the $2 billion poured into nanotechnology by these same agencies since 2000 [2]. In contrast to the earlier investments, this new Act specifically calls for a focus on the societal and ethical implications of nanotechnology (SEIN), and, during recent discussions, Congressman Brad Sherman advanced the idea that 5% of the total funding in the 2003 National Nanotechnology Initiative (NNI) budget should be devoted to study of SEIN. The House Committee on Science voted this down.

Still, research into SEIN remains an important part of the NNI; “Scientists and engineers bring to their work a laudable concern for the social value of their labors. However, those working in a particular technical field may be focused on the immediate technical challenges and not see all of the potential social and ethical implications... The inclusion of social scientists and humanistic scholars, such as philosophers of ethics, in the social process of setting visions for nanotechnology is an important step for the NNI” [3].

What is unusual about this emphasis on societal dimensions is that it is occurring while the new discoveries and inventions are being made — not after they have entered the broader society and begun to have effects that require mitigation and regulation. Advocates of SEIN studies point to the difficult reception for genetically-modified organisms (GMOs), a technology that promised a new green revolution but encountered resistance in Europe, Canada, and other parts of the world. The reasons for GMO’s difficulties are complex, but one major issue concerned an intense debate over the right to re-use engineered seeds. Monsanto and other companies wanted to protect their intellectual and financial investment in products like seeds with built-in pesticides. To do that, they developed a variety of strategies. Perhaps the most controversial was to utilize a gene developed by the U.S. Department of Agriculture, in collabora-
tion with Delta & Pine Land, that would “turn off” the desirable engineered trait after a single generation by preventing a crop from producing viable seeds, i.e., engineered infertility. The Rural Agricultural Foundation International (RAFI) labeled this “turn-off” trait a Terminator gene, raised widespread opposition to the development, and forced Monsanto and other companies to abandon plans to use it [4].

Recently, RAFI, which has now changed its name to ETC group,1 has entered the nanotechnology debate, proposing “that governments declare an immediate moratorium on commercial production of new nanomaterials and launch a transparent global process for evaluating the socioeconomic, health, and environmental implications of this technology” [5, p. 72].

The call by ETC for a moratorium on deployment of nanomaterials should be a wake-up call for nanotechnology (NT). The only way to avoid such a moratorium is to immediately close the gap between the science and ethics of NT. The lessons of genomics and biotechnology make this feasible. Either the ethics of NT will catch up, or the science will slow down [6, p. R12].

In this article, we describe a collaborative approach to SEIN research involving social and natural scientists, and discuss preliminary results. The team pursuing this research seeks to generate fundamental advances in nanotechnology that are simultaneously recognized for their consideration of the world community. We describe how this team has allowed concurrent consideration of SEIN issues and fundamental physical science questions to reshape the traditional path of natural science research. We also present a generic framework for initiating natural science research motivated and guided by societal and ethical considerations. One of the goals of this project is to establish that science-technology studies (STS) can play a positive role in shaping the research process, a collaborative version of the activism advocated by some STS scholars [7].

**Models of Technology Development**

To put the nascent efforts of our research team in context, consider three (out of many) possible models for the introduction of new technologies. Fig. 1 catalogues these models as: a) technological determinism, b) social goals drive research, and c) collaborate and iterate.

The technological determinism model, or Chicago World’s Fair motto, embodies the classic “throw it over the wall to society” approach to engineering, immortalized in the Tom Lehrer song about Werner Von Braun: “Once rockets are up, who cares where they come down? That’s not my department, says Werner Von Braun.” During the GMO debate, the so-called Terminator trait was seen by RAFI and others as an example of this sort of technological determinism.

![Fig. 1. The technology development process: Competing models.](image)

The second model, social goals drive research, was suggested, but not necessarily endorsed, by Henry Etzkowitz as an alternative to technological determinism [8]. Here society dictates the direction of research. Advocates of GMOs thought they were following this strategy; what could be wrong with a suite of products that promised to feed the world’s growing population while reducing the need for pesticides and herbicides [9]?

Although technological determinism and social goals appear to be very different approaches to directing scientific discovery, they share a common problem. In each model, one group or community is seeking to dictate to others; e.g., the engi-

---

1 An action group on erosion, technology, and concentration (ETC).
neers and scientists impose their view of nanotechnology on society or the ETC group imposes a moratorium on the developers of nanotechnology. Studies have shown this to be a common trait — socio-technical networks dominated by a single group prefer control to innovation. [10]-[12].

While many scientific initiatives can be categorized as following either the technological determinism or social goals approach, Fig. 1 also shows a third, collaborate and iterate approach, in which decisions about future technology are made by multiple stakeholders in constant dialogue. This model endorses the transparent process part of the ETC group’s approach without the moratorium. It implies that social scientists, ethicists, engineers, and natural scientists will work together at the “bleeding edge” of technology to generate advances endorsed by society.

A SEIN Nanotechnology Collaboration

At the University of Virginia, a social scientist (Gorman) and a materials scientist (Groves) have embarked on a nanotechnology research project designed to demonstrate that true interdisciplinary collaboration is possible. At the core of this study of the societal implications of nanotechnology has been a master’s degree research student (Catalano) whose project has been guided simultaneously by the social scientist and materials scientist.2 Since the co-advised masters degree student is conducting research that will lead to a Master of Science degree in materials science, she is focused upon synthesis and characterization of materials in much the same way as other materials science students might be. What distinguishes her basic science research project from those of many other materials science students is the emphasis placed upon consideration of the potential societal impact of her work, both the potential pitfalls and opportunities.

Having enunciated this distinction, what does it really mean to “consider the potential societal impact” of a science and engineering basic research project? In this particular study, the first implication has been the creation of a research team of different composition. Rather than including only materials scientists and researchers from related natural science disciplines in the discussions that set research priorities and targets, this team has, from the outset, included other stakeholders from the social sciences. The result is a collaborative and iterate approach to technology development in which one team member or the other proposes a next step and allows the others (i.e., natural and social scientists) to propose alternatives.

Secondly, the creation of this different interdisciplinary research team has led to the repeated intersection of societal impact considerations into the discussion. What often might have been at most an interdisciplinary natural science discussion now involves a broader interdisciplinary social and natural science discussion, with the co-advisors seeking to steer the project along a research path distinctly different than the one that would have been pursued if societal impact had not been considered so deliberately.

Thus, the third implication of this approach is that rather than focusing purely on natural science questions related to engineered material process – property relationships – the research team discussions have also explored questions related to the societal justification, concerns, and benefits of such research.

Why should society fund this research project? What benefit will society derive as the result of supporting this project? How might society use the results of this project? Will society’s use of these results be compatible with the ethical and moral standards of this research team? An inevitable outcome of this process is that team members have had to exercise moral imagination as they articulate and share their mental models.

Having raised these questions and committed to using them as guides for the project, the research team felt compelled to launch the discovery process from a different location. Thus, the fourth implication of this approach has been the construction of an additional layer of inquiry at the top of the research process. Rather than considering

---

2To keep a record of our thinking processes, all three participants have sent e-mail messages to a cognitive scientist [13], using as a model the diary he created as he became a molecular biologist (http://aracyc.stanford.edu/~jshrager/personal/diary.html). He would occasionally respond with queries designed to find out more about what we were doing and thinking. The result is a somewhat incomplete record of our decisions and records — incomplete because at this stage of the research, sending emails was voluntary. From this pilot, we hope to develop a more formal method for encouraging those engaged in SEIN research to provide records of their thinking and reflections.

---

Fig. 2. Simplified model of developing a research project based on a global problem or opportunity. Iteration would occur at each level.
only the material systems and properties that could be developed to make some new engineered devices, this team felt compelled to consider a space of possible “world ills” that could be mitigated by the creation of newly engineered nanotechnology devices (Fig. 2).

Note that, from the outset, the emphasis here is on the positive impacts of the technology development, not just avoidance of harmful ones. This model also looks like the “social goals drive research” approach in Fig. 1, but the difference is that all three members of the team collaborated on each stage, and iterated back to the first stage — the social goal — repeatedly.

Formally, the process of problem identification involves the addition of one more element to the collaborate and iterate framework described above: the notion of a problem space. Herbert Simon and his colleagues characterized scientific problem-solving as a search through multiple problem spaces, including possible hypotheses, experiments, and observations [14]. Bradshaw has described a variety of problem spaces used by inventors, including possible functions a device or component could fulfill and alternate designs [15]. In each instance, introduction of the concept of a problem space helps to reduce the possible workspace to a manageable set of alternatives as quickly as possible, and eventually to one solution path. That is exactly what was needed to define an appropriate SEIN Masters thesis topic for an engineering graduate student.

Using the apparent possibilities of nanotechnology, what engineered device could be created to mitigate one or more of the world’s recognized ills? Not only could such a research project improve the world through new discoveries that enable development of some specific engineered device but also it could provide a concrete example of the benefits associated with nanotechnology research and more specifically nanotechnology research that considers its societal implications during development. It also could act as a magnet for new research in this societally beneficial realm by advancing the state-of-the-art and providing insights that motivate others to capitalize upon this team’s successes.

In the particular case study pursued here, a problem space was created by overlaying a workspace of recognized world ills with a workspace of possible engineered devices that could mitigate such ills. In this particular case study, the engineered device was to harness the nanotechnology-based material properties of a specific material system for the purpose of mitigating a selected world ill. The nanotechnology constraint meant that at least one dimension of the device had to be in the 1-100 nanometer range, that the device’s design had to require control over processes at the molecular level, and that the underlying design could serve as the foundation of larger systems.³ The goal was to define the boundaries of the problem space so that a Masters thesis project could be initiated on one of a small set of identified material systems with the potential to deliver social benefits. If successful, this SEIN work should not only deliver new scientific knowledge upon which other natural scientists can build but also it should provide a process and framework that others can follow for the creation of completely different, socially beneficial technologies, nano or otherwise.

Creating the Problem Space
This way of framing the problem space evolved over the course of the project. The first step was to have the graduate student work on a list of candidate societal problems that

³This definition is adapted from one presented by Mike Roco of the National Science Foundation.
created opportunities for nanotechnology. Groves labeled these “world ills,” and the team evolved the idea of creating a listing of these “ills” and their associated “symptoms” (Fig. 3). The graduate student took the lead on the list, which iterated through several versions.

Study and discussion of the social science list of world ills made it obvious that the natural science aspect of the research could proceed in many different directions. While mitigation of certain world ills could involve development of a newly engineered sensor system (e.g., to detect a chemical, biological, or radiation hazard), other world ills research might seek to develop systems for purification (e.g., of ground water for drinking, of manufacturing plant effluent, or of fluids used in medical treatments). Still other world ills research might investigate newly engineered medications and delivery systems for improved human and biosphere health. In certain instances, it was unclear how nanotechnology research might make an impact upon a recognized world ill (e.g., gender disparity in education).

So, consideration of world ills still left the research team with a very large space of possible projects. One obvious constraint was the resources and expertise available to the team.

The team operated as part of the Center for Nanoscopic Materials Design, a National Science Foundation Materials Research Science and Engineering Center (MRSEC) established in 2000 to investigate the directed self-assembly of materials onto patterned surfaces. The members of this societal dimensions of nanotechnology project were already affiliated with the Center, and the Center’s research, which focused faculty investigations on related aspects of the same scientific challenge, presented a naturally collaborative environment. Inquiries from the societal dimensions team would be welcomed if the success of the selected world-ills project depended upon and possibly contributed to the Center’s ability to advance the forefront of scientific understanding in the field.

The Center for Nanoscopic Material Design studies directed self-assembly of quantum dots, primarily in the silicon-germanium material system. Researchers have reported the formation of quantum dots in semiconductor material systems in which a single crystal growth surface (e.g., a silicon substrate) and a depositing thin film (e.g., pure germanium) have the same crystal structure and a small lattice mismatch [22], [23]. The crystal structures of silicon and germanium (i.e., the arrangement of their atoms) are both diamond cubic, and pure Ge has a lattice constant (i.e., interatomic spacing) 4.1% greater than that of pure Si. Under carefully selected growth conditions, germanium will form small dots of material on the silicon surface, i.e., quantum dots. However, if nature is left to perform the process on its own, the dots generally appear at random locations across the substrate, e.g., like water droplets on the hood of a car. The Center is performing fundamental studies of how the growth location of dots can be specified to enable applications that demand dot placement in specific areas. Applications under consideration by faculty affiliated with the Center range from next-generation computer architectures to biological scaffolds built upon arrays of quantum dots.

This Center was supplying lab space and partial funding for the project, so it made sense to take advantage of the resources available — if they could be mated to one or more of the problems identified on the list. A third constraint was the physical science research expertise and interests of the materials science faculty team member (Groves) and the participating graduate student (Catalano). Groves had experience in working with metal oxides and Catalano indicated an interesting working with these materials in the laboratory. Gorman pushed at this point to keep a focus on societal benefits, asking why metal oxides made sense, aside from the interest of his colleagues. The literature suggests that metal oxides might be useful as a foundation for a bio-nano scaffold [24], the type of development that could mitigate several of the world ills identified in Fig. 3, e.g., terrorism, disease, or pollution.

So the team decided to go in that direction, but lacked the necessary bio-medical expertise. Therefore, the team added a biomedical engineer associated with the Center into the collaboration. His interest was in how endothelial cells lining the artery wall at the blood/tissue interface adapt to fluid mechanical forces that vary with time and place [16]. Breakthroughs in this area could lead to mitigation of atherosclerosis and potentially contribute to wound healing.

Use of Metaphors to Develop Research Strategy

To understand how the team incorporated the expertise of the biomedical engineer, it will be necessary to discuss the language core team members developed to communicate. Trading zone is a metaphor which has been applied to the development of various engineered systems like radar [17], magnetic resonant imaging [18] and other emerging technologies [11]. To develop radar, production-oriented engineers, theoretical physicists and military officers had to develop a creole, or reduced common language, that allowed them to trade knowledge and specifications. Engineers at the Jet Propulsion Laboratory use the term trade to refer to their negotiations over where to put a lander on Mars, and how to balance multiple design constraints among advocates who have different perspectives [19].

The scale of our collaboration is
much smaller than the design teams involved with radar or the Mars rover. Still, the three authors had to communicate across disciplines — a task made easier by the fact that one participant, the graduate student, was learning the languages of metal oxides, proteins, and global problems. The creole that evolved included shared meanings for common terms like “directed self assembly” and “problem space” — and had to be expanded to include biomedical terms.

To discuss the link between social goals and specific research targets, the team developed a metaphorical creole centered around the concept of hiking from a trailhead to the top of a mountain. In this creole, the specific engineered device selected by the team for research and development became a mountain. Unknowns identified by the team as barriers to delivery of the engineered device became streams or rivers that had to be crossed by bridges — new knowledge discovered during the course of the research. Creation of this creole allowed all team members to question goals — are we headed towards the right mountain — and strategy — are we building the right bridge? Fig. 4 shows the current state of this evolving metaphorical

Fig. 4. A process for development of science and engineering graduate student research projects, motivated by considerations of societal and ethical considerations. The actual process followed by this project is included in italics beneath each general step.
Successful Collaboration

A great deal of work remains to be completed before the end of this specific materials science Masters degree, and social and ethical issues will continue to play an important role. Still, the activities to date have been significant. By adding social and ethical discussions to every step of project development, an interdisciplinary team has been assembled that is distinctly different from the one that would have been pulled together had societal impact not been considered throughout. The team has initiated a project distinctly different from those typical for graduate students in the MRSEC and drawn in additional team members based on possible long-term benefits to society.

Once Gorman and Groves decided to use SEIN considerations to constrain the problem space, Catalano was able to create a chart of global problems, an expansion of the normal problem space considered by a nanotechnology graduate student. Subsequently, the problem space was further constrained by local resources and interests. Social issues continued to serve as a focus for project development through the use of a mountain-and-bridge metaphor, which functioned as a kind of creole. Finally, the team adopted a problem from biomedical engineering to serve as a bridge towards the range of mountains we had identified, one that would link to other bridges.

This research project constitutes proof-of-concept that social scientists and natural scientists can collaborate to identify a constrained problem that combines technical and social elements. It is too early to tell whether the result will be a technology that truly benefits society. However, the process by which the research problem is selected has been unique, as is the continuing dialogue over the societal implications of results. Members of the MRSECs advisory board noted that Catalano, the student involved with this project, was the only one of her peers who had an understanding of SEIN issues. As a result, the graduate students are now organizing a workshop on SEIN issues.

As the team moves towards the specific research of the Masters project, it is now confronted with new issues to consider. For example, should the team seek protection for any intellectual property that might be involved in its new engineered device design? Is intellectual property protection the most effective way to bring nanotechnology’s benefit to society? Here each team member must use moral imagination [20] to consider the perspective of other stakeholders and imagine alternate courses of action. What does each team member want to happen to this technology? How would the National Science Foundation, the University of Virginia, and the MRSEC like to see this project’s technology innovations advanced into the research and world communities? Who is most likely to benefit from patent protection, and who is most likely to be harmed? Over time these questions can be addressed through continued use of the collaborate and iterate model of cooperation.

Future Research

This small pilot project is, of course, only a first step towards the collaboration and transparent decision-making required if nanotechnology is to be of maximum benefit to society. In this case, it is hoped that the results of this project can be applied to multiple SEIN efforts at the University of Virginia and elsewhere, directed towards different societal “mountains,” used to explore how a network of bridges can be formed, and serve as the basis for cognitive diaries that record the process. In particular, we plan to encourage other research projects in different domains of nanotechnology to consider societal dimensions from the earliest stages. A larger base of researchers and graduate students will make it possible to conduct a summative evaluation while preserving the anonymity of the participants. As a first step in this direction, the biomedical engineer is making this project part of a larger trading zone that is forging links between nanotechnology and tissue engineering.

To improve collaborations like this one, more social and ethical expertise should be added early on. We encourage having a scientist or engineer collaborate with an ethicist or social scientists, but we would
recommend a panel of other experts in societal and ethical dimensions be available for consultation. At the University of Virginia, such a function will be carried out in the future by a Nanotechnology Working Group of our Institute for Practical Ethics; this working group was formed in response to the need to expand this pilot project and to develop more sophisticated strategies for directing research towards social benefits.

It is also difficult for a graduate student to work alone on such a project. The ideal would be to establish a group of such graduate students, some from technical disciplines, some from humanities and social sciences. Each nanotechnology student would be paired with one from a social sciences or ethics; they would jointly pursue research of the sort described here, with advisors from multiple disciplines. These students would have others engaged in similar projects to talk to.

In addition, we need a mechanism for adding stakeholders from industry, consumers and those traditionally underserved by technology. Consensus conferences and scenario workshops provide one model [21], thought these have typically focused on broader socio-technical issues like urban ecology, genetically-modified organisms and attention-deficit disorder, not the research direction of a particular project team which may have intellectual property concerns. One solution is to form the right kind of an advisory board for research projects, one that includes representatives of stakeholders likely to be affected by the result.

It could be argued that the current project succeeded in part because Groves and Gorman were unusually willing to collaborate. Future research will have to engage into the process natural scientists, engineers, social scientists, and ethicists who do not initially see the point in doing collaborative research with a SEIN focus. We hope that this pilot project will encourage others to make the attempt. At the very least, the discussion of impacts makes all project members think harder about why they are doing what they are doing. At best, it produces discoveries and inventions that are more likely to represent social as well as technological progress.

Author Information
M.E. Gorman is with the Dept. of Science, Technology and Society, J.F. Groves is with the Department of Materials Science and Engineering, and R.K. Catalano is with the School of Engineering and Applied Science, at the University of Virginia, Charlottesville, VA, 22904.

Acknowledgment
This research was made possible through support of an NSF NIRT Award on Societal and Ethical Implications of Nanotechnology (SES-0210452) and an NSF MRSEC Award to the Center for Nanoscopic Materials Design at the University of Virginia (DMR-0080016).

References