PROMETHEUS^{-9}: IMPLICATIONS OF NANOTECHNOLOGY AS PERCEIVED BY NANO-SCIENTISTS

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by

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ABSTRACT

This thesis uses material from interviews with faculty and graduate students working with nanomaterials at Brown University to examine questions related to the benefits, liabilities, and ethical, legal, and social implications of nanotechnology. Our title reflects the claim currently being made that in engineering materials on the nano-scale (the prefix "nano" denotes 10^{-9}) we are transforming the building-blocks of life, and ultimately the way we all live. We find that although understanding of the benefits, liabilities and implications of nanotechnology among members of the scientific community and the understanding of nanotechnology among members of the public differ in several ways, these divergent perspectives can be reconciled significantly through the clarification and communication of several key concepts prevalent in both the scientific and social-scientific literature. Furthermore the dissemination of these core concepts can aid in the facilitation of dialogue among stakeholder groups as we seek to develop a precautionary approach to the regulation and development of nanotechnology.

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I. Introduction

A. Nanotechnology: What's At Stake

Despite its increasing prominence in the scientific, regulatory, and public spheres, there is still no single definition of "nanotechnology". In essence, nanotechnology refers to the production, manipulation and use of materials at the scale of 100 nanometers or less (Davies 2006; National Research Council 2002). At this scale, materials behave unexpectedly, exhibiting properties that differ physically, chemically, and biologically from their larger counterparts. Although much of nanotechnology is still in the research and development phase, nanomaterials are expected to be used in a wide variety of applications ranging from biomedical drug delivery to electronics, pollution remediation, and less toxic modes of manufacturing (Baird and Vogt 2004). Many scientists and policy-makers see nanotechnology as the wave of the future, and, as a result, investment in nanotechnology has continued to increase.

In the U.S., the National Nanotechnology Initiative (NNI) is a federal, interagency research and development program coordinating 25 agencies, including the Food and Drug Administration, the Department of Defense, the National Science Foundation, the Environmental Protection Agency, and the Department of Homeland Security. NNI is scheduled to receive over $1.2 billion in the President's 2007 Budget (National Nanotechnology Initiative 2006), which is more than triple the annual investment the initiative received in its first year and will bring the total investment in the NNI to over $6.5 billion since its establishment in 2001. The global impact of products where nanotechnology will play a role is expected to exceed $1 trillion by 2015 (Einsiedel and Goldberg 2004; Roco 2003).

As nanotechnology research races forward, both occupational and public exposure to potentially harmful nanoparticles will undoubtedly increase (Dreher 2004). At present, innovation in nanotechnology applications is proceeding ahead of related policy and regulation, raising concerns that ethical, environmental, economic, legal, social, and toxicological research is lagging behind (Mnyusiwalla et al. 2003; Einsiedel and Goldenberg 2004; Renn and Roco 2006). The conflicts foreseen for nanotechnology are nearly as wide and varied as its many promises. These include issues involving discrepancies between international, federal, state, and agency regulations, intellectual property concerns, and privacy issues, in addition to more traditional health and safety concerns. While the Nanotechnology Environmental and Health Implications Workgroup (NEHI) works to prioritize research regarding human and environmental health implications, the EPA is addressing nanotechnology with a holistic approach—researching beneficial applications while developing risk assessment and management strategies (Karluss et al. 2006).

Researchers argue that due to differences in size, shape, surface area, chemical composition, and biopersistence, engineered nanomaterials should be assessed separately from their larger counterparts for environmental and human health impacts (Hoet 2004). A better understanding of nanomaterials is also crucial because, as Colvin (2003) describes, the current lack of technical data on the safety of nanomaterials "provides fertile ground for both nanotechnology proponents and skeptics alike to make contradictory sweeping conclusions about the safety of engineered nanoparticles" (p.1166). Indeed, in the current debate opinions vary widely from the "nano-radicals" who imagine that nanotechnology will ultimately be responsible for the production of countless materials; to “nano-realists” who focus on incremental innovations; to the “nano-skeptics” concerned the risks that self-replicating nanomaterials could pose to humans and the environment (Wilsdon 2004). Of course, there are a wide range of opinions in between these positions, but the fact remains that the uncertainty surrounding nanotechnology has left scientists, regulators, and the public without clear guidance regarding the safety of these increasingly widespread materials.

Researchers have found that, due to the unique ability of nanomaterials to travel vast distances in air, water, and the human body, crucial information on nanotechnology is lacking for each step of risk assessment—there are significant gaps in toxicological data, exposure routes, health effects, and current and future production levels (Powel and Kanarek 2006). However, extensive research on exposure to ultrafine particles and asbestos, both of which have many significant similarities to certain nanomaterials, provides a strong foundation for understanding the mechanism by which the inspiration of nanoparticles can be more dangerous than that of their larger counterparts (Holsapple et al. 2005; Kane 2007). Carbon Nanotubes (CNTs) are of particular concern because they already exist in the environment in soot, air pollution, and as combustion byproducts. Furthermore, due to their high physical strength, flexibility, and conductivity, CNTs are used in a range of applications including electronics and display devices, biomedical research, food and agricultural products, and sporting goods, exposing both manufacturing workers and customer end users to these potentially toxic materials (Powell and Kanarek 2006a; 2006b).

CNTs also raise concern because their long fibrous structure is similar to that of asbestos, another “miracle” material which was later found to have extreme deleterious effects (Tsuji et al. 2006). This structural similarity suggests that the two materials might have similar mechanisms of toxicity when inspired. Indeed, several “red flags” have already been raised that seem markedly similar to concerns regarding asbestos exposure. The available literature suggests that inspired CNTs have unusual toxicity properties when compared to larger respirable particles (Donaldson et al. 2006). CNTs seem to have a greater ability to stimulate mesynchymal cell growth than their larger counterparts, causing granuloma formation and fibrogenesis. Furthermore, as with asbestos some of the toxic effects of CNTs might be achieved through oxidative stress and inflammation. However, the mechanisms by which CNTs cause their deleterious health effects are still poorly understood (Donaldson et al. 2006).

Because of their ubiquity and the greater number of risk assessment studies that have been conducted relative to other nanoparticles, CNTs can provide insight into the precautionary measures that might be taken in regulating nanomaterials given the current state of scientific knowledge. Of particular concern is the threat of exposure through inhalation, as nanoparticles can be easily emitted and suspended into air from both stationary and mobile combustion sources (Biswas and Wu 2005). When inspired, larger particles tend to remain in the upper respiratory airways. Although this can indeed be damaging, ultrafines pose an even larger threat due to their ability to travel deeper into the alveolar regions of the lungs where gas exchange occurs (Powell and Kanarek 2006b). For this reason, respiratory toxicity studies of nanoparticles have been prioritized in evaluating the overall health implications of nanomaterials.

Several animal studies on the respiratory toxicity of CNTs have already been conducted (Hucksko et al. 2001; Lam et al. 2004; Warheit et al. 2004; Muller et al. 2005;

Shvedova et al. 2005), and the available animal evidence suggests that carbon nanotubes are capable of eliciting a granulomatous, inflammatory, fibrogenic response when inhaled into the lungs (Tsuji et al. 2006). This has the potential to hold enormous implications as environmental and occupational exposure to manufactured nanomaterials including CNTs increases in the near future, and should raise concerns regarding the long-term health implications of the increasing use of nanomaterials in consumer products, industry, and pharmaceuticals (Dreher 2004; Powell and Kanarek 2006a).

In addition to preliminary toxicology research, many cite previous biotechnology debates surrounding genetically modified foods, asbestos, and lead in order to argue that precaution is important both in terms of environmental and human safety as well as in establishing positive "public relations" for nanotechnology (Einsiedel and Goldenberg 2004; Mehta 2004; Macoubrie 2006). While some have called for outright bans until more data has been collected, others argue that the benefits of nanotechnology outweigh these potential costs, and, thus, research should move forward while "real-time technology assessment" continues (Sweet and Strohm 2006; Baird and Vogt 2004; Royal Society and Royal Academy of Engineering 2004). However, both groups agree that in order for nanotechnology to achieve its many promises, a better understanding of the toxicity of nanomaterials must be achieved.

B. The Regulatory Status Quo: Many Agencies, Little Action

In September of 2000 the National Science Foundation (NSF) established the National Nanotechnology Coordinating Office (NNCO) and determined its role in monitoring potential risks of nanotechnology, including social and ethical issues likely to arise with the emergent technologies (Roco 2003). NNCO is also charged with communicating with the public and addressing unexpected consequences that may arise. Furthermore, two bills for nanotechnology were submitted in the 108th Congress aimed at addressing the need for interdisciplinary multi-agency planning with regard to nanotechnology. The first of these bills, the "21st Century Nanotechnology R&D Act" (S189), which recommended a five year "National Nanotechnology Program' (now the National Nanotechnology Initiative), passed in December of 2003. The second bill, the "Nanotechnology Research and Development Act of 2003" (H.R. 766), which authorized NSF funding of multi-agency research ($424 million in FY 2006), passed in May of 2003 (Roco 2003). However, despite the laudable work done by the NNI along with the Nanotechnology Environmental and Health Implications Workgroup (NEHI) in supporting environmental health and safety research and outlining prioritization strategies for research in the future, many gaps remain in both nanotechnology regulation and risk management, leaving the public, workers, and the environment largely unprotected from potentially toxic materials (Karluss et al. 2006).

Today, nanomaterials already on the market have not been studied for toxicological effects, nor has there been a systematic collection of information regarding these materials (Powell and Kanarek 2006b). Renn and Roco (2006) outline deficits in current risk governance of nanotechnology, including: below-optimal measurement and assessment of the presence and characteristics or nanomaterials in the workplace and the environment; a lack of environmental health and safety knowledge; fragmented governmental institutional structure and legal authority; weak 'coordination' of safety issues among stakeholders; limited knowledge of social, ethical and legal implications; a dearth of resources targeted at better risk governance in R&D budgets despite the fact that there are no published or standardized risk assessment tools; and, lastly, an overconfidence in our ability to regulate or remediate exposures after the fact.

As alluded to in Renn and Roco's list of risk governance deficits, some of the current issues in the regulation of nanotechnology arise from conflicts and discrepancies between federal and state agency laws (Sweet and Strohm 2006). There are a number of existent laws that have the potential to cover nanotechnology regulation. Because of its broad jurisdiction over chemicals defined as "any organic or inorganic substance of a particular molecular identity," some have argued that nanomaterials should be regulated under the Toxic Substances Control Act (TSCA) (Davies 2006). The use of this statue becomes significantly more complicated when attempting to determine whether or not nanomaterials would fall under TSCA criterion based on the "significant new use" rule since most nanomaterials are not, in fact, new chemicals. However, the significant new use rule requires that a material be produced in a volume in excess of 10,000 kilograms per year, which means that in order for nanomaterials to fall under this jurisdiction an exemption from this volume requirement would be necessary (Davies 2006). Furthermore, TSCA assumes that an absence of knowledge about a chemical means that there are no risks, which would, therefore, promote little action in the face of uncertainty (Davies 2006). TSCA is not the only regulation that claims jurisdiction over nanotechnologies—other potentially applicable regulations include: the Occupational Safety and Health Act, the Food, Drug and Cosmetics Act, the Clean Air Act, and the Consumer Product Safety Act (Davies 2006). As a result, these jurisdictional conflicts among agencies are nearly as diverse and complex as the technologies themselves.

C. The Current Challenge: Prioritization of Risk Research

With the ever-present allure of nanotechnologies' many applications, little of the NNI's increasing budget is being used to fill in data gaps in toxicology, epidemiology, eco-toxicology, and occupational safety (Powell and Kanarek 2006b). However, if the beneficial applications of nanotechnology are to be realized, both toxicological and ethical research needs to keep up with the more heavily-funded R&D research being done now. Because nanomaterials are so varied and widespread, one of the first steps is to prioritize what toxicity and risk research should be done first. In November, 2006, Andrew Maynard and a number of other leading nanotechnology researchers published a plan for prioritizing risk research in the next 15 years. They began by stating that:

> As research leaders in our respective fields, we recognize that systematic risk research is needed if emerging nano-industries are to thrive. We cannot set the international research agenda on our own, but we can inspire the scientific community—including government, industry, academia and other stakeholders—to move in the right direction (p.267).

The plan outlined challenges and gaps in current risk research to be filled-in in a timely fashion so that nanotechnology research can safely and successfully move forward.

However, as a result of these remaining gaps in toxicological research, debate continues over what should be done in the interim periods while this research is being conducted. Some argue that the precautionary principle should be applied which, as outlined by Raffensperger and Tickner (1999), suggests that, "when an activity raises threats of harm to human health and the environment, precautionary measures should be taken if some cause-effect relationships are not fully established scientifically" (p.353-354). Such an approach would involve interim risk management actions to restrict human and environmental exposures to nanomaterials, as well as a required demonstration of the safety of nanomaterials *prior* to their being placed on the market. However, while proponents argue that an application of the precautionary principle is the only way to be protective of both public and environmental health, others counter that it could only result in an outright ban on the introduction of nanotechnologies into commerce, thereby impeding beneficial applications (Sweet and Strohm 2006).

D. Current Social and Ethical Implications (SEI) Research: Public Relations or Public Participation?

Despite remaining concerns regarding the lack of regulation of nanomaterials themselves, there have been some promising developments in the approaches being taken to nanotechnology development as compared to the early phases of previous technological revolutions. Many SEI researchers have cited the debate surrounding the use of genetically modified organisms (GMOs) as an example of an emerging technology which posed challenges similar to those of nanotechnology both in terms of scientific uncertainties as well as difficulties in establishing positive public relations (Einsiedel and Goldberg 2004; Mehta 2004; Macoubrie 2006). The scientific and industrial communities involved with GMOs saw negative public perception lead to resistance to the use of the technology as well as a backlash with severe economic consequences (Sandler 2006). With GMOs these scientific uncertainties and negative media portrayals were accompanied by a lack of communication regarding risk management, which led to a feeling that public concerns were being ignored and a lack of understanding regarding the risks and benefits of the technology (Sandler 2006).

As a result of a general increase in the consideration of the implications associated with scientific and technological developments, as well as the oft-cited GMO-analogy, academic and industry researchers alike have developed social and ethical implications components to their projects. Sandler and Kay (2006) describe, the NNI "explicitly calls for assessment of the social and ethical dimensions of the nanotechnology revolution and public engagement regarding it, concurrent with scientific and technological advances" (p.676). There is a growing body of social and ethical implications (SEI) literature related to the development and implementation of nanotechnologies. While much of the earlier literature was more of a predictive nature—asking questions related to the, then, primarily hypothetical use of nanomaterials to improve the human condition, SEI researchers now begin to turn their focus toward a very real consumer market for realized applications.

Much of the emphasis in the SEI research being conducted, however, has fallen upon public participation and education, with more than a dozen studies conducted on public perceptions of nanotechnology as of 2006 (Cobb and Macoubrie 2004; Currall et al. 2006; Berube 2006). Researchers are now voicing concerns regarding the nature of these efforts, arguing that too much focus has fallen on education rather than dialogue, and that pertinent ethical issues remain overlooked. Some worry that this focus on public perceptions is aimed at developing a strong public relations strategy for the implementation of nanotechnologies, and does not take advantage of the opportunity to openly discuss the use of materials about which so little is still known.

This thesis seeks to add to a growing body of knowledge regarding what will constitute relevant and meaningful SEI research in the field of nanotechnology. One of the central goals of SEI research has been to help ensure "democratic participation" in the development of nanotechnology research goals and regulations. However, in reviewing the SEI research being conducted it is clear that while the public is continually polled and surveyed for their opinions regarding nanotechnology, there has been little research of this nature involving members of the scientific community who are undoubtedly valuable voices in representative decision-making processes. Furthermore, as this thesis' findings suggest, this oversight will hinder meaningful dialogue among the diverse fields of science involved in nanotechnology research, as well as among industry, regulatory agencies, and the public, and, as a result will take away from our ability to realize the potential of nanotechnologies in a safe and effective manner.

II. Data and Methods

This study is part of a multidisciplinary project at Brown University funded by the National Science Foundation as part of its program on collaborative research in nanoscale science in engineering under the Nanoscale Interdisciplinary Research Teams (NIRT) program. This project addresses the toxicity, biocompatibility, and practical health and exposure risks associated with a range of modern nanomaterials, as well as the societal impacts of new nanomaterials with a special focus on risk perception and university nanomaterial safety. The research team has principal investigators in the physical, biological, and social sciences who work with environmental, health, and safety professionals at Brown to formulate nanomaterial safety guidelines for university research laboratories and disseminate those guidelines through web posting and special training programs. Furthermore, the cross-disciplinary educational component of this project trains graduate students to have an increased awareness of the societal, ethical, and human health implications of new nanotechnologies.

As part of this project, environmental health, and safety (EHS) professionals at Brown administered a survey to identify all of the labs involved in nano-scale research at the University. Members of the social science research group then conducted interviews with the 18 faculty and 21 graduate students identified. The study was intended to be an examination of the perceptions of the "universe" of researchers at our university, and, thus, inferential statistics are not presented to make claims about a larger population.

Interview Schedule. Interview questions were constructed based upon reading of social and ethical implications (SEI) literature relevant to nanotechnology, with additional input from the larger environmental health research group of which the SEI team is part, and with an outside expert in SEI. The interview was then piloted with one research participant. Two members of project team conducted the first two interviews together in order to refine the technique and give consistency to the interview process. The remainder of the interviews were conducted by two researchers between March and December of 2006

Interviewees were asked approximately thirty questions about the social, ethical and legal implications of nanotechnology. The interview schedule was comprised of five subject areas: (1) specifics of individuals' research, (2) general knowledge and attitudes towards nanotechnology, (3) regulatory issues, (4) ethical considerations, and (5) risk assessment. Interviews typically lasted between a half-hour and an hour and fifteen minutes.

Analysis. All interviews were tape recorded and transcribed, except for two who refused to be recorded. Notes were recorded after each interview. Transcripts and postinterview notes were imported into NVivo 7, a qualitative data management and analysis tool. NVivo was used to code patterns and themes in the interviews using an initial list of codes that were identified following a review of the transcripts and based on categories of questions used in the interviews and on the issues of interest that were identified in the literature. Data analysis was done in an iterative fashion, with additional readings of the transcripts leading to additional codes and to recodes, as more was learned. NVivo allows the researcher to code entire files with certain characteristics such as demographic variables, then specify which value the variable must have for the file to be selected in the search. NVivo uses the selection feature in combination with the code count to construct matrices that can be looked at as they are, or imported into statistical packages such as SPSS for quantitative analyses.

Codes were divided into six major categories: (1) analogies used by interviewees, (2) benefits and applications, (3) liabilities and risks, (4) ethical implications, (5) perceptions of public understanding of science, and (6) discussion of the precautionary principle. To ensure consistency, all final coding was completed by one researcher, and the accuracy and consistency of coding was reviewed for several sample transcripts by additional members of the research team. NVivo was also used to assign “attributes” to the interview transcripts identifying the status (professor or graduate student), and areas of training of the participants (toxicologists and non-toxicologists, and those involved in biological versus material sciences) as seen below in Table 1. All quotes that appear in this paper are from interviewees; they are identified by the numbers assigned to their transcripts.

Table 1: Status and Areas of Training

	# of Sources/N=39	%
Professors	18	46
Graduate Students	21	54
Toxicologists	11	28
Non-Toxicologists	28	72
Biological Sciences	12	31
Material Sciences	27	69

III. Results and Findings

A. Benefits and Applications

The benefits and applications of nanotechnology (shown in Table 2) discussed by the interviewees aligned closely with those projected by both the National Nanotechnology Initiative, as well as those in the media and popular press.

Table 2: Benefits and Applications[i]

	# Respondents	%
Biomedical	33	85
Electronics	17	44
Materials Applications	17	44
Drug Delivery	15	38
Energy	9	23
Researchers and Industry will benefit	7	18
Optics	5	13
Catalytic Applications	4	10
Environmental	4	10
Cosmetics	3	8

[i] In this and other tables the number of respondents will not total to 39 as a single interviewee can refer to multiple categories over the course of the interview.

The emphasis fell most heavily on biomedical applications (N=33; 85%), with 15 (38%) of the interviewees specifically mentioning drug delivery. Biomedical applications were followed by electronics and materials applications, both with 17 (44%) interviewees referencing their potential. Furthermore, all interviewees (39; 100%) felt that the benefits of nanotechnology could potentially accrue to many people, as expressed both by identifying groups such as "consumers," "computer-users," or "the public in general," as stakeholders in nanotechnology, as well as several statements similar to one graduate student's claim that "nanotechnology is the future" (BGS003).

B. Liabilities and Risks

Over the course of the interviews, all participants (N=39), indicated some liabilities and risks associated with the use of nanomaterials and nanotechnology (Table 3), although several interviewees (10; 26%) felt that these risks were no different from risks associated with common lab practices and materials.

Table 3: Liabilities and Risks

	# of Respondents	%
Human Health	35	90
Environmental	26	67
Risks are unknown or not fully understood	25	64
Abuse	13	33
Risk depends on type of NM	10	26
Risks like other risks	10	26
Technology-specific	10	26
Unknown IS the risk	10	26
Catalytic reactions	3	8
Fire and Explosion	3	8
Risk of industry going bust	2	5

The majority of interviewees (25; 65%) accurately indicated that the risks and liabilities associated with nanomaterials remain unknown, or are not yet fully understood. However, an even greater majority felt that nanomaterials could pose a risk to human health effects (35; 90%) and the environment (26; 67%). Thirteen participants (33%) felt that there was a potential for abuse of nanotechnologies, however, this was often mentioned in tandem with the ten (26%) assertions that these risks were not inherent in anything "nano," but rather, are similar to risks associated with other technologies.

Interviewees again echoed much of the toxicology literature, in the ten (26%) mentions that risks and liabilities will vary on the type of nanomaterial being used. And, thus, it is unsurprising that ten (26%) participants also felt that the risks would be technology-specific.

Interestingly, ten interviewees (26%) also argued that the fact that risks associated with nanomaterials are unknown is a risk in and of itself. As one graduate student remarked:

> I do think there are risks mostly because no one's really ever investigated these materials, and I would be suspect of any materials whether or not it's nanomaterial or something large if its effects hadn't been investigated (BGS001).

A number of researchers also indicated specific human health effects that may be associated with nanomaterials. Table 4 (below) extends the previous table to include these specific risks.

Table 4: Human Health Risks

	# of References	%
Human Health	35	90
Inhalation and Respiratory Risk	24	62
Occupational hazards	24	62
Dermal	15	38
Chronic risk	14	36
Blood stream	6	15
Risk to consumers	6	15
Genetically transmissible	1	3

Inhalation and respiratory risks (24; 62%) were by far the most common health effects mentioned in our interviews. This was expressed both as a liability of nanomaterials in general, as well as something to be aware of in risk management in the laboratory.

Twenty-four (62%) participants also mentioned that there were risks associated with nanomaterials in the lab and workplace, although only six (15%) mentioned that nanomaterials could pose a risk to consumers.

Given the fact that many of the promised applications of nanomaterials, such as treatment of central nervous system disorders, rest upon their oft-cited ability to easily cross biological barriers, it was surprising to find that only six (15%) interviewees mentioned a risk of nanomaterials getting into the blood stream (Mnyusiwalla et al. 2003). This is especially notable given the current discussion of nanomaterials' ability to translocate from the lungs into other parts of the body (Kane 2007). As a result of these disparities, we chose to examine differences in risk perception by academic status (graduate students vs. professors), and areas of training (material sciences vs. biological sciences, and toxicologists vs. non-toxicologists). Although we found slight differences between the graduate students and professors, and those involved in biological and material sciences, the largest differences were found in comparing toxicologists and non-toxicologists (Table 5).

Table 5: Toxicologists vs. Non-Toxicologists Risks and Liabilities

	# of References	Toxicologists	% of Tox.	Non-Toxicologists	% of Non-Tox
# of Sources/N=39	39	11	100	28	100
Human Health	35	11	100	24	86
Environmental	26	10	91	16	57
Risks are unknown or not fully understood	25	10	91	15	54
Disposal	14	4	36	10	36
Abuse	13	5	45	8	29
Risks like other risks	10	1	9	9	32
Technology-specific	10	3	27	7	25
Unknown IS the risk	10	5	45	5	18
Risk depends on type of NM	10	5	45	5	18
Catalytic reactions	3	1	9	2	7
Fire and Explosion	3	1	9	2	7
Risk of industry going bust	2	1	9	1	4
NT is safe	1	0	0	1	4

Toxicologists were more likely than non-toxicologists to mention both environmental and human health risks associated with nanomaterials, with 100% (11) of toxicologists and only 86% (24) of non-toxicologists mentioning human health risks, and 91% (10) of toxicologists and only 57% (16) of non-toxicologists citing risks to the environment as a liability of nanotechnology.

As previously mentioned, one of the central arguments for taking a precautionary approach in the regulation and application of nanomaterials is that the risks associated with these materials are still unknown. Thus, it is significant that while this fact was salient in the interviews with those involved in toxicology research, only slightly more than half of the non-toxicologists mentioned that the liabilities associated with nanomaterials are not yet fully understood. This suggests that this is a concept that should be better disseminated throughout the involved scientific community. In addition, toxicologists (45%;10) were more likely than non-toxicologists (18%; 5) to perceive these unknowns *as* risks. The notion that risks will depend on the type of nanomaterial being used was also more prevalent among toxicologists (45%, and 18% of non-toxicologists). As will be discussed later, identifying differences in risks associated with particular nanomaterials will be critical to developing these technologies in a way that is both safe and economically successful and, thus, should be emphasized and shared across scientific disciplines. Lastly, while 32% (9) of the non-toxicologists felt that the risks associated with working with nanomaterials were like other risks, only 9% (1) of the toxicologists felt this to be the case.

C. Ethical Implications

Despite an interview schedule that actively targeted some of the ethical implications of nanotechnology dominant in SEI literature, the implications raised by interviewees were markedly dissimilar (Table 6).

Table 6: Ethical Implications

	# of Sources/N=39	%
Abuses	13	33
Equity	11	28
Medical	10	26
Animal testing	9	23
Research ethics	7	18
Safety unknown	7	18
Environmental	6	15
Privacy concerns	2	5
Legal	1	3

Implications of environmental exposures, medical ethics, privacy concerns, equity, as well as legal, regulatory, and insurance issues dominate much of the SEI literature around nanotechnology, (Baird and Vogt 2004). While some of the concerns prevalent in our interviews, such as abuses of nanotechnology (13; 33%), and issues around human health and medicine (10; 28%) aligned with the literature, many of the concerns seen as pressing in the SEI community, were much less commonly cited. Privacy (2; 5%) and legal (1; 3%) issues did not often arise in our interviews. Furthermore, although 11 participants (29%) felt that issues of equity could be problematic, only 2 (5%) of the participants cited equity concerns prior to our question regarding a potential technological and economic gap between countries with and without certain nanotechnologies, referred to as the "nano-divide" in common parlance and in the interview schedule. As will be discussed later, this also served as an example of an area in which the implications that arose most often among scientists were markedly different from those being raised by members of the public in surveys conducted thus far (Macoubrie 2005).

In conducting our interviews, we reflected on the need to "translate" the notion of ethics in multiple senses of the word. Firstly, a significant portion of the population interviewed (14; 36%) were not native English speakers. As a result, 8 interviewees (21%) were unfamiliar with the English word "ethics.[1]" This is not to say that these individuals do not, in fact, consider ethical implications of nanotechnology as they are understood by social-science researchers. However, it does indicate a limited ability to discuss such issues in the research community. Furthermore, as seen in Table 7, those familiar with the English term for ethics were more likely to discuss all areas of ethical implications than those who were unfamiliar with the word. Again, this is likely a result of English language fluency, but has the potential to stifle meaningful dialogue among scientists and stakeholder groups if it is not explicitly acknowledged and addressed. The

[1] Indicated by request for clarification of the word ethics, for example, "I'm sorry, what do you mean ethical?" (BGS003).

unfamiliarity with this term found in these interviews is perhaps indicative of a lack of such discussion thus far.

Table 7: Ethical Implications Divided by Those Unfamiliar/Familiar with the Word "Ethics"

	# of Sources Unfamiliar with Ethics	% (# of Sources/N=8)	# of Sources Familiar with Ethics	% (# of Sources/N=31)
N=39	8	100	31	100.0
Abuses	2	25	11	35.5
Equity	2	25	9	29.0
Medical	2	25	8	25.8
Animal testing	1	12.5	8	25.8
Safety unknown	1	12.5	6	19.4
Environmental	0	0	6	19.4
Privacy Concerns	0	0	2	6.5
Research ethics	0	0	7	22.6

Furthermore, the word "ethics" takes on yet another meaning in the context of many of the interviews—with several of the participants associating the word with issues of academic integrity (7; 18%), and animal testing (9; 23%). This is not to argue that these issues are unimportant or that they should not fall under the scope of ethical considerations of nano-scale research enterprises, the prevalence of these issues in the interviews indicates a need to actively "translate" a more broad-based nuanced notion of ethics in conversations among social-scientists, scientists, and the regulatory community.

This need to clarify "ethics" is further supported by the numerous mentions of abuse as a potential ethical concern. As one professor described: "You can always dream up some negatives that some evil-doers could use this for, but if we trust the fundamental good of people we'll always, you know, try to bring up, to use these things in a positive way. Yeah, some bad guys build an atomic bomb" (BP003). Although concerns regarding abuse are indeed important, there is a danger of missing many of the more subtle ethical concerns if this is what is emphasized. Furthermore, the association of our questions regarding ethics with "mad scientists in the back room…bent over these test tubes of all different colors and making, you know, doomsday devices" (BGS001), as one researcher put it, could stifle potentially beneficial conversations between social and research scientists. Furthermore this could promote a kind of C.P. Snow (1959) culture divide between sciences and the humanities, or, worse, between scientists and everyone else, especially given the value of researchers' voices in promoting new technologies.

Many of the interviewees reflected on the nature of ethics considerations in the research community more broadly. Although not on a quantitative level, several other themes emerged from these conversations. First, several researchers noted that current ethics training courses are dominated by "publication and research ethics" (BGS001), and "the way you train engineers and scientists to think does not by its nature include ethics" (BP015). Furthermore, based upon both observations as well as comments made by some of the participants, it is evident that many scientists, as people, "do worry about these things" (BP015), however there is little forum for discussion of broader ethical issues among scientists.

Some interviewees also reflected on possible reasons for the lack of ethical discussion among scientists. Funding and prestige can hinder a scientist's ability to consider these issues—as one scientist said regarding consideration of discussion of risks in the scientific community: "They won't give the Nobel prize for something like that" (BGS025). Furthermore, for many researchers, these issues are uncomfortable or burdensome to consider—as one graduate student stated: "Ethics is a gray area, scientists don't like it" (BGS025). However, all researchers felt that science, at large, could be a tool for positive social change.

D. Analogies

Given the prevalence of analogies to previous issues of science, technology and health in the literature on nanotechnology, it was useful to examine the use of analogies in our interviews as a way of understanding how researchers perceived these same issues. Twenty of the interviewees (51%) employed analogies to illustrate benefits, liabilities, and social and ethical implications surrounding the development and use of nanotechnology (Table 8).

Table 8: Analogies Used

	# of Sourves/N=20	%
Asbestos	11	55
Stem Cells	5	25
Genome Projet	3	15
GMOs	3	15
Internet	3	15
AIDS treatment	2	10
Cigarettes	1	5
Plasticizers	1	5
Nickel in Orthopedics	1	5
Recombinant DNA	1	5
Tissue Engineering	1	5
Ultrafines	1	5
Whisker-Based Materials	1	5

Given both the common use of asbestos as an example of an environmental-health disaster, as well as the research interests of some of the primary investigators on campus, it was unsurprising that asbestos, with 11 sources (55%), was by far the most commonly used analogy. However, in order to best understand the use of the other analogies employed, we identified the "use" of each analogy by finding the intersections of the analogies, and the implications they were used to discuss divided into areas of: risks and liabilities, ethical implications, benefits and applications, public understanding of science (PUS), and the precautionary principle (PP) (Table 9).

Table 9: Use of Analogies

	Risk Analogies	Ethical Analogies	Benefit Analogies	PP Analogies	PUS Analogies
Analogies-- Total	11	9	4	3	2
Asbestos	9	1	1	1	1
Stem Cells	0	5	0	0	0
GMOs	0	1	0	1	1
Internet	0	1	1	0	0
AIDS treatment	0	1	0	1	0
Genome Projet	0	1	1	0	0
Cigarettes	1	0	0	0	0
Nickel in Orthopedics	1	0	0	0	0
Plasticizers	1	0	0	0	0
Recombinant DNA	0	0	0	1	0
Tissue Engineering	1	0	1	0	0
Ultrafines	1	0	0	0	0
Whisker-Based Materials	1	0	0	0	0

Analogies were used by the greatest number of interviewees (11; 28%) in order to discuss risks and liabilities associated with nanotechnology, then followed by those who used them to discuss ethical implications (9; 23%), benefits and applications (4; 10%), the precautionary principle (3; 8%), and public understanding of science (2; 5%). While asbestos is by far the most cited analogy overall, it is primarily employed to discuss risks and liabilities, whereas analogies used to discuss broader contextual issues (ethical, public understanding, or precautionary approaches) were more varied.

Stem cell research emerged as the dominant analogy in discussing ethical implications (5; 13%). Notably, stem cell research is an area in which the dominant ethical concerns are very much tied to issues of right-to-life and beliefs about manipulation of biological materials, and is one in which exposure and health concerns are not yet consequential. Here, much of the sentiment seems to be that social and ethical concerns are holding back potentially beneficial research. It is also of note than only three (8%) of the interviewees used GMOs as an analogy. This is surprising given the prevalence of the analogy to the European GMO backlash in the SEI literature, and the use of this analogy to support a precautionary approach to nanotechnology research and development. Furthermore, it serves as another example of the discontinuity between public understanding of technologies, and the dominant understanding of the implications of these technologies among members of the scientific community.

E. Novelty, Continuity and Risk:

At the very core of the field of nanotechnology is the argument that, at the nano-scale, particles exhibit properties that are significantly different physically, chemically and biologically from their larger counterparts (Davies 2006). Indeed, it is likely based on these novel properties that several of the researchers we interviewed felt that nanotechnology research represented the future of science and technology on the whole. Wilsdon (2004) points out that in addressing uncertainties in nanotechnology risk assessment it is important to identify sources of "novelty and continuity," meaning that in order for nanotechnology to be effectively communicated, researchers must be able to identify ways in which these materials differ from their larger counterparts, and in what ways they are the same.

Themes of "novelty and continuity" were salient in conversations with researchers. While most researchers touted applications based upon novel properties of nanomaterials, many also expressed concern that it would be irrational to regulate things on a nano-scale while ignoring their micro-scale counterparts. For example, in discussing the concerns of some environmental groups about nanotechnology, one professor pointed out: "[there's] not really any reason I can think of why the size of those grains being ten nanometers is any different if they're ten microns, a thousand times bigger. Right?" (BP015). Another professor echoed this sentiment with respect to ethics: "I guess if you go from the micron-scale to the nano-scale, I don't see the big difference in ethics if you show me something that's micron by micron or if you show me something that's ten nanometers by ten nanometers" (BP010). This does not intend to suggest that these views are not well-founded, nor that they contradict the promised applications of nanotechnology; rather, it is intended to highlight the need to explicitly address such seeming inconsistencies in the public sphere.

One possible mechanism by which this might be addressed is through differentiating different types of nanoparticles and nano-based materials. This is being actively advocated in the field of nanotoxicology (Hansen 2007) as it will be crucial in developing applicable regulation and risk assessment. As previously mentioned, several interviewees also suggested that risks and liabilities associated with nanomaterials are dependent on the type of material (10; 26%) and that ethical implications will be dependent on specific technologies (10; 26%). Furthermore, these issues were often cited in discussion of the breadth and ambiguity of the words like "nanomaterials" and "nanotechnology." Although the goal of our interview schedule was to capture a range of responses, many interviewees found it challenging or frustrating to identify benefits, liabilities, and implications of something as broad as "nanotechnology."

Nearly half of the participants (18; 46%) reflected on the need to define and differentiate between nanomaterials. Some interviewees reiterated the prevailing toxicological view that defining the novel features of nanomaterials will be crucial to developing effective risk-management strategies. One professor stated with respect to environmental health and safety practices in the lab: "What they have to define is…how does [sic] nanomaterials differ from existing chemical guidelines and how should they be handled?" (BP006). Others felt that definitional issues would impact public perceptions of nanotechnology. Another professor noted:

> They are now taking their current materials that they're implanting and calling some of them nanotechnology, which it's not nanotechnology, and they're using it of kind of an advertisement ploy, and I think that's a big disservice to the field because it makes this definition more loose and fuzzy and nobody really knows then what nanotechnology is (BP015).

F. The Precautionary Principle

The majority of participants were unfamiliar with the precautionary principle as presented in our interview schedule. The precautionary principle, in its application to nanotechnology regulation, would mean that there is a presumption of risk associated with the use of nanomaterials until research demonstrates their safety. This is contrasted with the more typical approach in the United States of presuming new materials to be "innocent until proven guilty," or rather, safe until negative health effects are demonstrated. Although only three interviewees (8%) thought the use of the precautionary principle would be a bad approach to regulating and developing nanotechnology in the US, and twenty-eight researchers (72%) felt that it would be a useful approach, there was a lack of clarity as to what such this might entail (Table 10).

Table 10: Perceptions of the Precautionary Principle

	# of References	%
Good approach	28	72
Halting or slowing research	16	41
Precaution only at application phase	6	15
Interprets as conservative approach	5	13
PP wrong approach	3	8
We are already using PP	2	5
PP too costly	1	3

Several interviewees (6; 15%) felt that the precaution would only be appropriate as technologies move away from theoretical science and into the application phase, which avoids much of the spirit of the precautionary principle which suggests taking action early-on in the development of technologies. Three (8%) noted with respect to their particular research, that it was too “theoretical” or “fundamental” to regulate in such a manner. Further confusion existed over what research might look like under a “precautionary regime.” Five (13%) interviewees interpreted the precautionary principle as taking a generally cautious approach to research (as one researcher described, “it’s always good to be cautious in your research”) while, on the other end of the spectrum, one professor expressed concern that an application of the precautionary principle would put a stop further toxicology research. Two researchers (5%) also felt that we are already using the precautionary principle in research in the US, which, again, suggests that they might understand an application of the principle to be somewhat different from models that exist in the social-science literature.

The bulk of the concern regarding the precautionary principle, however, centered around issues of halting or slowing research (16; 41%), which has been a central issue for those who oppose the use of the precautionary principle. While some interviewees were personally concerned about the effects that such an approach would have on their research, others felt that it would be a good approach, but that overall trends in research and economic incentives would overshadow the benefits. As one graduate student reflected:

> I think from a species survival level the precautionary principle definitely seems to be a smart approach. From an economic development and revenue level it may be hindersome. It may slow down some of the developments that could take less time if they were conducted with less care, with less foresight (BGS004).

Several researchers were also aware of potential sources for the concerns voiced by precautionary principle advocates, both in terms of the “scientific” risks of nanomaterials themselves, as well as from a more historical perspective. One professor described what have been referred to as “late lessons from early warnings” (European Environmental Agency 2001):

> On the other hand, it’s [the use of the precautionary principle] obviously based on some fairly awful things that have happened in the last 20, 30 years, or even longer—people who have rushed into things prematurely have created problems. So it’s hard to say that people are necessarily overreacting (BP015).

G. Public Understanding of Science

Opinions were varied as to how much the public understands and knows about “nanotechnology” on the whole, as well as the benefits and liabilities associated with nanomaterials (Table 11).

Table 8: Perceptions of Public Understanding of Science

Public:	# of References	%
Doesn't understand nano	24	62
Unaware because nano not at application phase	11	28
Desn't understand for lack of information	10	26
Generally uneducated about science	9	23
Aware of nano-products	6	15
Aware of some liabilities	4	10
Unaware of nano altogether	4	10
Aware of nano broadly	3	8
Aware of German recall*	2	5

* Refers to a recall of a “Magic Nano” bathroom cleaning product by German officials in April of 2006 as a result of reported respiratory problems thought to be associated with its use.

While a majority of the interviewees (24; 62%) felt that the public does not understand nanotechnology, only four (10%) felt that the public is unaware of nanotechnology all together. Interviewees identified a number of potential sources of this lack of understanding. Eleven participants (18%) felt that the public is unaware of the benefits or liabilities of nano-science because much of the research is not yet at the application phase. Ten participants (26%) also identified a lack of information being openly disseminated (by government, scientists, or the media) as a source of public unfamiliarity. As one professor stated: “I think there’s… an administration that’s not pro-science, certainly not pro-biological research, and I just think that maybe scientists haven’t done a good enough job of maybe communicating to the public about technology” (BP006).

Furthermore, several participants (9; 23%) situated public ignorance and misunderstanding of nanotechnologies in the broader context of a public that is unaware of advances in science and technology in general. Many of them traced “scientific illiteracy” to a lack of education, and some expressed concerns that this may give rise to exaggerated perceptions of both the risks and liabilities of nanotechnology—a concern that echoes both the SEI literature on the GMO-nanotechnology analogy, as well as industry and government concerns regarding “nano-hype” (Berube 2006). A pathology professor explained:

> I think when people don’t understand science or health issues in any systematic or rational way, they’ll grasp onto anything to help them grapple with these complex things. So I think that, for example, you’ll look at people’s ideas about some types of health issues and diseases and the origin of diseases and treatment of diseases. I think because they don’t have a fundamental understanding of the sciences, they develop these very strange almost folk-scientific beliefs to substitute. And I think that’s a failure of our education and our society (BP001).

IV. IMPLICATIONS

A. From Public Understanding of Science (PUS) to Scientist’ Understanding of the Public (SUP)

One of the primary arguments for addressing social and ethical implications of nanotechnology early-on has been that if the public comes to associate nanotechnology with “toxic risk” it will undermine the benign benefits of nanomaterials (Colvin 2003; Mnyusiwalla, Daar and Singer 2003; Einsiedel and Goldberg 2004; Sandler 2006). Furthermore, Parr (2005) argues that one of the central lessons to be taken from the GMO analogy is that public attitudes towards technology are “not driven by ‘risk’ in the scientifically understood sense of hazard and probabilities” but are, in fact, “much more about institutional and cultural responsibilities” (p.386). Thus, it is important to identify similarities and differences in how the public and scientists perceive nanotechnologies and their implications, as well as some of the dominant perceptions of the public’s scientific knowledge among members of the scientific community.

Not surprisingly, the analogy most interviewees used to understand the risks and implications of nanotechnology was the case of asbestos exposure. This is likely tied to the structural analogies being drawn between asbestos fibers and carbon nanotubes in the current scientific literature (Huczko et al. 2001; Murr and Soto 2004; Soto et al. 2004; Warheit et al. 2004), in addition to the research interests of nanotoxicologists at Brown University. However, references made to asbestos by researchers were also likely tied to the abundance of scientific evidence demonstrating the toxicity and deleterious health effects associated with asbestos exposure (U.S. EPA 1984; Moyer et al. 1994; Manning et al. 2002). This may suggest that researchers understand implications and risk not in terms of institutional response, but, rather, in terms of scientific toxicology and risk assessment, which is further supported by their use of the “asbestos analogy” to discuss risks and structural similarities rather than the social context in which these materials and technologies exist. This can be seen in the references to asbestos made by one graduate student and a professor in their respective interviews:

> And then, of course, the classic example of asbestos fibers, which are not… necessarily nanomaterials, but those are air borne… and those that are air borne are inhaled and dangerous. So they really need to be investigated (BGS001).

> They [nanomaterials] are similar in many ways to naturally-occurring minerals such as crystalline silica, or asbestos fibers, and I think we really have to systematically study the properties of these new materials as they're developed to ascertain how similar or different they really are (BP001).

Members of the public have also employed the "asbestos analogy" to discuss implications of nanotechnology. In one 2005 study conducted with a total of 177 participants in three U.S. cities, asbestos, along with other past regulatory, environmental, and human health errors, was mentioned by participants in order to express concerns about nanotechnology (Macoubrie 2005). However, findings of this study suggest that much of the public concern related to asbestos centers around oversight processes designed to manage risks, in addition to health effects. Addressing these apprehensions will be crucial to gaining public trust, as the asbestos legacy is one riddled with industry cover-up and regulatory inaction (Tweedale 2002). Macoubrie proposes that some of the public suspicion may arise from a lack of information, which is further illustrated by the use of what she refers to as potentially "misleading" analogies such as: dioxin, Agent Orange, or nuclear power.

We are at a unique moment in the development of nanotechnology. As one of the researchers involved in conducting an NSF-funded online survey of 1,800 persons in 2007 stated:

> The U.S. public's perception of nanotechnology is up for grabs. It could divide along the lines of nuclear power, global warming and other contentious environmental issues absent a major public education and engagement effort by industry, government, civic groups and scientists. People who know little or nothing about 'nanotechnology' instantly react

> in an emotionally charged way to the concept, and their opinions divide along cultural lines as they learn more about it (Dan M. Kahan, as cited in Nanowerk 2007).

Furthermore, while public education could be valuable in the development of nanotechnology in terms of avoiding a GMO-like backlash, dialogue among scientists, government, industry, and members of the lay-public will be necessary for true public engagement as well as necessary regulatory foresight (Moor 2005; Sandler and Kay 2006).

Indeed, research on the social and ethical implications of nanotechnology continues to be conducted in both U.S. government and academic institutions to a much greater extent than with previous technological developments. However, some have expressed concerns that some social and ethical implications research serves as public relations strategy, rather than as a facilitator for dialogue. Berube (2006) says, of the SEI efforts of the National Nanotechnology Initiative: "it doesn't take a linguist to read the subtext: nanotechnology will improve the US economy, and we must find a way to integrate it smoothly into the current economic infrastructure" (p.317). The emphasis on education of the public, and lack of dialogue "fails to appreciate the limits of science and industry" and will detract from responsible and successful nanotechnology development (Sandler 2006).

Sandler (2006) suggests that the role of SEI research should be to help facilitate this process of public engagement. The focus of SEI facilitation, however, should not fall solely on translating "technical" ideas to members of the public. In order for dialogue to succeed, the public needs to communicate with the scientific and technological community familiar with relevant ethical issues. This has led some researchers to argue for greater discussion of SEI in science and engineering education, and, as a result, "nano-specific" ethics courses are being taught and actively developed. One course, which integrated ethical components with more traditional engineering elements of the curricula in order to avoid isolating ethical considerations, was taught by members of this research team to graduate and undergraduate students in the Spring of 2006. Two rounds of surveys were administered to the students in the course, and the findings, suggested that: (1) students felt more strongly about ethical implications following their completion of the course, (2) students felt that such a course would be helpful to other involved researchers, and (3) the interdisciplinarity of the course was valuable to those involved (this research will be reported shortly).

While such courses are undoubtedly valuable, they do not necessarily address what we see as another potential obstacle to dialogue—scientists' understanding of the public (SUP, a play on the often-discussed "public understanding of science," or PUS). Even in these early stages of nanotechnology development, forums for dialogue among stakeholder groups, such as the "nano-cafés" at the University of Wisconsin-Madison, have already arisen (Citizen's Coalition on Nanotechnology 2007). Forums of this sort could help to identify concerns held by members of the public and scientific communities, and help to clarify areas in which these concerns overlap and diverge, and point to possible sources of misunderstanding and miscommunication among stakeholder groups. Furthermore, it is hoped that such dialogue will help improve not only the public reception of emerging nanotechnologies, but also help to incorporate a wide array of concerns into policy making as these issues are addressed on the regulatory level.

It is important seek to identify concepts and ideas that could be better communicated among stakeholder groups (including various scientific disciplines, and members of the public and regulatory communities), as well as the potential role for SEI researchers in disseminating these concepts. As Berne (2006) points out, scientists often function inside of "somewhat cloistered communities" (p.35). However, as we found in our conversations with researchers, Berne argues that the intent of most of the research scientists and engineers she interviewed "is to contribute conscientiously to the ethical development of our nanotechnology future" (p.36). Thus, we hope that by accurately communicating key concerns and concepts among involved groups, the voices of concerned researchers can be more meaningfully included in ongoing discussions regarding nanotechnology development and regulation.

i. Scientist vs. Public Core Concerns:

It is crucial to acknowledge that neither "science" nor "the public" are monolithic, and, thus, do not speak with one voice. Yet it also true that scientists do share a certain background of professional training, and, thus, in these discussions there were certain core concerns that differed significantly from those being raised by members of the public in preliminary nano-related PUS research. As previously discussed, many of the interviewees expressed the feeling that the public at large is "scientifically illiterate", or unaware of research and developing technologies. While the perception that much of the public has low awareness of nanotechnology at this point in time is reflected in public perception research (Macoubrie 2005's study found 54% of the public knew "almost nothing", 17% "knew something", and 26% knew "a little" about nanotechnology, and 60% of the 1500 survey respondents in Waldron et al.'s 2006 study had never heard of “nano”)—this current gap in understanding should not be interpreted to mean that the interests of the public and research communities with respect to nanotechnology are at odds.

In fact, following the NNI’s Public Meeting on Research Needs in January 2007, the Committee on Nanoscale Science, Engineering and Technology (NSET) released a press statement with the headline: “Public Shares Views on Environmental, Health, and Safety Research Needs for Engineered Nanoscale Materials” (2007). Furthermore, when comparing the core concerns held by the researchers in this study with the concerns raised by members of the public in Macoubrie 2005’s study, they overlap significantly (Table 12).

Table 9: Scientist vs. Public Core Concerns about Nanotechnology Development (rank ordered by most frequently reported concerns in descending order)

Scientist’s Concerns[ii]	**Public’s Concerns**[iii]
• Human health risks	• True unknowns
• Environmental risks	• Regulatory concerns
• True unknowns	• Human health risks
• Risk depends on type of nanomaterials	• Testing and research for safety
• Technology-specific risks	• Effect on environment
• Abuse	• Food & food chain concerns
• Catalytic reactions	• Industry irresponsibility
• Fire and explosion	• Privacy
• Risk of slowing or halting research	• Military uses, international political instability
• Risk of the industry going bust	• Playing God, messing with Mother Nature
• Messing with some of the building blocks of life	• Economic access & education
• Regulatory concerns	• Consumer knowledge & information
• Equity concerns	• People centered goals for progress
	• Taxpayer cost of development
	• Fearful people stopping good
	• Mistrust of government in general
	• Social upheaval & adjustment

[ii] From Brown University study, N=39
[iii] Macoubrie 2005, N=426

Human and environmental health risks associated with nanotechnologies, as well as “true unknowns” regarding the behavior and nature of nanomaterials, were prevalent among scientists and members of the public. Perhaps surprisingly, concerns of slowing research, or, as referred to in Macoubrie's study, "fearful people stopping good," were present in both groups. As mentioned, regulatory issues, and those of industry and corporate responsibility are pressing concerns for members of the public, but were not as commonly brought up in our interviews. Thus, scientists and corporate stakeholders must struggle with questions that cannot be addressed by science alone, but, rather, they must publicly incorporate social and ethical concerns into the development and regulation of nanotechnologies in order to ensure the greater public trust necessary for their success (Gaskell et al. 2005). On the other hand, scientists were more aware of differences in risks posed by various types of nanomaterials, as well as the potential for risks to vary with specific applications. Disseminating information regarding these variations in risks can help inform regulation and drive public acceptance of benign applications of nanotechnology.

ii. Classification and Differentiation

As described in Maynard et al.'s proposal for nanotechnology risk governance, differentiating and classifying nanomaterials according to their associated risks will be crucial for expediting the implementation of these technologies without unnecessarily exposing workers and the public to materials with negative health effects. Indeed, we found many researchers, especially those involved in toxicology, are aware of the range of risks associated with different nanomaterials. However, classification and differentiation of nanomaterials and their risks should not be done behind the closed doors of labs or government institutions. As toxicological research already shows, some nanomaterials are likely to have deleterious health effects (Hansen 2006, unpublished). Thus, if consumers or members of the public have no knowledge of how these materials differ, they are likely to be wary of beneficial applications. Researchers and regulators should work to communicate to the public these variations in risk and the "unknowns" associated with certain types of materials, as well as concepts of "novelty and continuity." Furthermore, such discussion could provide an opportunity for better communication among groups of scientists, and to regulators, leading to safer lab practices and more accurate interim risk management strategies. As previously discussed with respect to carbon nanotubes, current evidence is suggestive of certain deleterious health outcomes. However, the current research also highlights the many unknowns that still remain, especially with respect to what properties of nanomaterials will be relevant to their toxicity. Thus, actively outlining and classifying this research will be beneficial to scientists, regulators, and members of the public alike.

iii. the Precautionary Principle

It is not likely that the precautionary principle in its truest form is well-understood by members of the public nor, as seen in our study, by researchers involved in nanotechnology. Traditionally, it has been unpopular as a regulatory idea in the US, often opposed on the grounds of being either costly or slowing research. However, because of the biopersistent nature of nanomaterials, mounting toxicological evidence, and the lessons from "miracle materials" of the past, the argument for its application is particularly strong in the world of nanotechnology. In fact, due to the nature of these materials, some leading toxicity researchers have been compelled to step out of the bounds of traditional research science to plead for the application of precaution in order to avoid a potential health disaster (Muller et al. 2005; Kane 2007). In the conclusion to a paper on lung toxicity of multi-walled carbon nanotubes Muller et al. (2005, p. 230) state:

“Based on these initial observations, the precautionary principle should be applied and adequate industrial hygiene measures implemented to minimize human exposure during the manipulation of carbon nanotubes.”

Given the economic potential of nanotechnologies, as well as their diverse applications in the areas of environmental and human health, it will not be easy for regulators, industry stakeholders, scientists, and members of the public to come to a consensus with regard to how much “precaution” should be applied as we move forward with nanotechnology. Furthermore, none of these groups are monolithic; among scientists, just as among members of the public, there exists a wide range of opinions as to what will constitute such a balance. However, in order to initiate such a discussion, it is crucial that SEI researchers aid in clarifying the nature of the precautionary principle and its implications. Some of the perceptions of the precautionary principle in the scientific community, such as the notion that all toxicity research would be stopped, are so extreme as to restrict any dialogue surrounding the use of this approach without proper clarification.

Here I highlight four elements of the precautionary principle: preventive action, burden of proof, exploring alternatives, and democratic participation, (1) as they might be implemented in a “precautionary approach” to nanotechnology regulation, (2) present in our interviews with researchers, and (3) how these approaches and findings might be integrated.

1. **Preventive Action:**

Taking preventive action in the management of risks associated with nanotechnology will require a multi-faceted approach. Clearly, such action should entail a prioritization of toxicological research (such as that outlined by Maynard et al. 2006). Furthermore, it requires a proactive management of risks while this research is being conducted. This means that there should be interim risk management based on the assumption that nanomaterials are indeed toxic until further research demonstrates otherwise (Denison 2006). Interim risk management actions should occur both in the workplace by completing worker training to prevent worker exposure, and in the environment by restricting any dispersion of nanoparticles until there is data available on their environmental fate and toxicity (Denison 2006). As more research is conducted, it is also crucial that researchers differentiate between classes of nanomaterials so that they can be regulated as such, which will help avoid unnecessary future clean-up and remediation costs and foster the acceptance of nanotechnologies (Biswas and Wu 2005).

Although the scientists we interviewed often invoked the possibility that a full-on application of the precautionary principle might hinder research, they were invariably averse to the idea of addressing risks only as an after-thought to technology-development. Researchers consistently expressed the need to conduct more toxicology research, and acknowledged that risks and liabilities of nanotechnology were, in fact, unknown. Furthermore, several interviewees were concerned with or had already implemented interim risk management strategies such as those described by precautionary proponents either to restrict exposure to workers in the lab, or prevent open release of nanomaterials into the environment. However, the successful implementation of preventive action will indeed rely on the willingness of regulators and industry stakeholders to fund toxicity research and weigh the costs of "slowing research" against those of exposing humans and the environment to materials with unknown effects and paying for costly cleanup.

Furthermore, several involved scientists were open to the idea of taking time to assess the toxicity of materials.

2. Burden of Proof:

As previously mentioned, nanomaterials are already being used in a number of consumer products despite the fact that their safety has yet to be demonstrated. This is especially troubling given the biopersistence of nanomaterials. Although government regulatory agencies should continue to fund broad-based nanotoxicity research, manufacturers of products containing nanomaterials should be charged with demonstrating their safety *prior* to their being placed on the market. With certain nanotechnologies, such as drug delivery applications, this will be an obvious step for their respective regulatory agencies (FDA). However, safety should be demonstrated for all consumer applications. This should not be taken to mean that the use of nanomaterials in consumer products is to be banned, but, rather that toxicity research is to be prioritized, and that in the absence of data the manufacturers should conduct such research.

Although researchers interviewed in this study were a bit more conservative, there was an overall sentiment that nanotechnology should be regulated by government or industry prior to going on the market (even in the interviews where precaution was interpreted by the interviewee as just a cautious approach). For cost reasons this might be an area where there is some divisiveness, but the researchers readily agree that safety should certainly not be an afterthought to nanotechnology applications. However, another point of contention might arise from which applications are significant enough to warrant such forward-looking research. Whereas sunscreens containing titanium nanoparticles that are not easily inhaled, but could be easily washed off into open bodies of water may be seen by some as worth evaluating, others feel that this type of product does not represent the “real applications” of nanotechnology. Again, this “burden” could be more easily alleviated and shared with proper classifications of materials. In Hansen’s (2006 unpublished) review of 177 studies on a total of 393 studies, he found there to be a lack of characterization of the nanoparticles studied, which makes it difficult to link specific properties to observed health effects, as well as hindering extrapolation of research finding. As a result, Hansen applies a categorization framework of nanomaterials to a “hazard identification scheme aimed at identifying causality between inherent physical and chemical properties and observed adverse effects” (p.2).

3. Exploring Alternatives:

One of the primary claims of nanotechnology proponents is that nanomaterials will help us to solve a number of public health and environmental problems we face today. Although this is undoubtedly an exciting possibility, this should not be used as an excuse to expose the public to substances with unknown and potentially detrimental health effects. Furthermore, this argument ignores the possibility that there might be a number of other less toxic ways of meeting these needs. As a result, research into alternative ways to achieve these goals should be promoted in both the public and private sector. For example, there should be continued research aimed at enabling the development of alternative and sustainable energy sources outside of the realm of nanotechnology (Biswas and Wu 2005).

It is not surprising that few researchers focused viable alternatives to the technologies they were involved in developing during our conversations, especially given the dominant feeling of excitement and promise around their projects. However, some did reflect on science's abilities to produce alternatives. When asked about whether or not he felt the precautionary principle might impede research, one professor replied: "It might slow it down a little, but… it would be a good thing. In my career I've seen things go from lab to industry. It might be a shock for half a year, but people would come up with more safe ways. They don't want to kill their workers." Indeed, many researchers, including some involved in our study, have now turned their attention to evaluating "alternatives" within the realm of nanotechnology. It is hoped that studies conducted early-on in nanotechnology development identifying relationships between the material structure and composition of nanomaterials to their toxicity can be used to guide development of "green" nanomaterials (Kane 2007).

4. Democratic Participation:

The traditional models of cost-benefit analysis that scientists have used to account for ethics in the development of technology do not confront the considerations raised by ethicists, social scientists, and the public. As a result, researchers who fail to account for these concerns may be risking both the success of their grant applications in the present as well as the success of the technologies they hope to develop in the future (Moor 2005). Furthermore, traditional models of ethical consideration have involved the public only as a technology moves towards its "power stage," when the technology is already readily available and integrated into society (Moor 2005). As was seen with GMOs, this late incorporation of ethics can lead to a massive backlash with harsh economic consequences, especially given that so much money had already been invested in the development and production of the technologies. However, the early consideration of the ethical and social dimensions of nanotechnology should not be aimed solely at avoiding public resistance, but, rather, should acknowledge that although industry and the scientific community bring technical and economic expertise to the development of technology, they cannot claim to be experts in the social and ethical elements of technological development (Sandler 2006).

Democratic participation in decisions surrounding nanotechnology could, and should, take many forms. One of the first steps should be to allow consumers to make their *own* decisions by instituting a labeling requirement for products containing nanomaterials. Although it is likely that debates over mandatory and voluntary labeling will emerge as more nanoproducts are produced, this is a necessary step in lieu of a ban of products without demonstrated safety (Mehta 2004). However, the processes of public engagement and deliberation should be moved ‘upstream’ within nanotech R&D, and not just occur at the stage of consumer exposure (Wilsdon 2004). As Wilsdon (2004) comments, “from focus groups to referenda, citizens’ juries to deliberative mapping, there are as many processes for public involvement as there are technologies to debate” (p.21). Given the broad and expansive applications of nanotechnology, the forms of democratic participation should be just as diverse, including basic internet-based documentation of research and information, as well as the incorporation of public opinion on the desirability of specific applications of nanotechnology (Renn and Roco 2006). Furthermore, government regulatory actors should take care to provide the public with information on the principles used to test the safety of nanotechnology products (Renn and Roco 2006). As Renn and Roco (2006) describe: “If people have the reassurance that public authorities take special care and attention to protect the population against unintended consequences of this new technology, they may be willing to invest some more trust than today in the capacity of society to control risks and be aware of and responsive to remaining uncertainty" (p.182). Developing such risk communication strategies will be challenging. However, it is crucial that consumers be included in decision-making as they are undoubtedly stakeholders in a field with so many marketable applications (Maynard et al. 2006).

Many scientists were indeed aware that more can and should be done to help members of the general public better understand emerging technologies (in the field of nanotechnology and in science in general). And, in fact, there is a growing body of work suggesting that US government, academic, and regulatory institutions are beginning to make an effort to both educate members of the public, and seek out their opinions in this rapidly expanding field. However, "democratic" participation will require overcoming perceptual barriers in order to foster communication among stakeholder groups.

Sandler (2006) makes use of what he terms the "GMO (dis)analogy," to develop four possible lessons for incorporation of public participation and the role of SEI research in the development of nanotechnology (adapted into Table 13). However, the scientists involved with nanomaterials on a daily basis possess a unique perspective that should not be forgotten in these discussions. Sandler emphasizes that while elements of the "very shallow" and "shallow" lessons are being currently implemented, it is the "deep" and "very deep" lessons that will result in meaningful engagement. Thus, we seek to add to the latter two lessons in areas where this situated knowledge of researchers should be accentuated, and, additionally, areas where SEI research can be used bi-directionally to communicate and "translate" both techno/scientific and socio-cultural areas of concern.

Table 10: Lessons for Public Engagement Adapted from an article by Sandler (2006, p.60).

	Public Engagement	**Role of SEI Research**
The very shallow lesson	• Allow public to air concerns • Explain and educate public about technologies, their potential, risk management, and regulation	• Identify public concerns • Develop methods for public communication • Be involved in public education effort • Demonstrate that those involved in development of technologies share SEI concerns
The shallow lesson	• Very shallow lesson, plus: • Public participation in risk management decision-making	• Very shallow lesson, plus: • Develop mechanisms for such public participation • Ensure regulatory capacity is capable of enforcing resultant decisions
The deep lesson	• Shallow lesson, plus: • Provide open forums or other mechanisms through which concerns about NT can be collaboratively explored (i.e., inclusive of public, ***science industry***, regulatory community, and SEI researchers) • Results will inform risk management and R&D (e.g., by setting funding priorities)	• Shallow lesson, plus: • Develop public participation mechanisms • ***Facilitate and enrich this process by providing expertise on identifying, clarifying, articulating, and evaluating SEI concerns***
The very deep lesson	• Deep lesson, plus: • Forums in which public's desires for NT, positive and negative, can be articulated, explored, and evaluated • Democratic process to set objectives for NT as well as funding priorities or constraints • ***Scientific community and industry, then, can attempt to develop viable technologies to realize these objectives and constraints***	• Deep lesson, plus: • ***Provide expertise on identifying, clarifying, articulating, and evaluating possible objectives for, and constraints on nanotechnology research and application***

In creating forums for collaborative exploration of concerns about nanotechnology, facilitators should be conscious of including a range of representatives from "science industry." In a field as diverse as nanotechnology, and as seen in these interviews, "science" does not speak with one voice. It will be particularly important to ensure representation of those involved in both biological and material sciences, as well as those conducting toxicology research. Furthermore, an effort should be made to include researchers of varying "ranks." As found in the interviews, several graduate students were unfamiliar with "ethics" as a concept. Involving these researchers in these conversations has the capacity to increase familiarity with SEI concepts among this population, and emphasize the importance of ethics in the next "generation" of scientists. Additionally, as reflected upon by many of the primary investigators we interviewed, it is the graduate students who come into the most intimate contact with these materials, which gives these students particular knowledge of their properties, and, furthermore, enhances their "stake" in safety evaluations.

As indicated in Sandler's "very deep lesson" technological development and funding should be prioritized based upon conversations among stakeholder groups. However, the "objectives and constraints" should undergo continual evaluation to avoid unnecessarily stifling research, and, furthermore, so that they are not perceived as products of a public-driven limitation of research within the scientific community. This trend towards democratic participation in the setting of funding priorities has the potential to seem stifling to traditional "experts." However, as discussed, the concerns and hopes of scientists and members of the public for nanotechnology are, in fact, more closely aligned than either of these groups might imagine.

SEI research already has an unprecedented presence in the development of nanotechnology. Thus, it is worthwhile to identify more precisely how this research can contribute to discussions of nanotechnology's development and interim regulation. As argued by Sandler and Kay (2006), the focus of SEI research should move beyond education and toward enhancing dialogue. This means that SEI research should not only seek to clarify SEI concerns in general, but should target specific areas of interest that are the particular focus of a given stakeholder group or area of scientific research, as well as clarifying concepts that have multiple meanings and can easily be "lost in translation." This should include:

- Articulating toxicologically significant properties of nanomaterials including their biopersistence, and ability to translocate within the body.
- Differentiating between research ethics, and broader considerations of ethical implications—this will be especially important in communicating and evaluating "ethics components" of academic and government research. Furthermore, SEI researchers should differentiate between classes of "ethical considerations" in a model similar to that of Berne (2006) who delineates three "dimensions" of "nano-ethics" in order to differentiate between concerns regarding potential abuses of nanotechnologies, and ethical concerns regarding human and environmental health exposures to materials with potentially deleterious effects. In Berne's model first dimension ethics apply to "widely held standards" such as safety protocols and risk assessment (she gives *primum non nocere*—'first do no harm' as an example of first dimension ethics) (p.79). Second dimension nano-ethics are about contestable moral claims, such as questions of distribution, and, lastly, third dimension ethics contain the "meta-ethical" questions regarding human life, self-hood, and beliefs about existence (p.88). Such an explicit differentiation can help clarify what it means to address ethics in the research and development of nanotechnologies.
- Novelty, continuity, and risk should be continued topics of discussion as they are of immeasurable value to researchers developing proper laboratory procedures, government agencies seeking to prioritize future research and create interim regulations, and the public both in terms of understanding nanotechnology as a whole, and differentiating between classes of materials in order to make informed choices as consumers.
- Outlining the precautionary principle, and facilitating discussion of its implications as well as potential forms of implementation. Here, it will be especially critical to underscore the importance of continued toxicity research in "precautionary approaches" to technology.

- Underscore the importance of regulatory and institutional contexts of developing technologies in fostering public trust and acceptance, in addition to areas, such as environmental health and safety, where public, regulatory, and scientific concerns coincide.
- Unknowns and areas of uncertainty—although these are often the most challenging areas to clarify, all stakeholder groups must collaborate to continually identify what is and is not known with respect to nanomaterials and their safety in order to accurately evaluate the costs and benefits inherent in choices we as a society make in the promotion and regulation of nanotechnologies.

Lastly, as seen in discussions with scientists from a wide array of fields, toxicologists possess a unique knowledge of the health effects and implications of the materials they handle, and, thus, their participation should be ensured on several levels. First, as argued by Maynard et al. (2006), a greater percentage of nano-related funds should be directed toward toxicology research in the early phases of development. Second, toxicologists and material and biological scientists should collaborate in order to both ensure the safety of researchers, as well as to include health and safety considerations in the early on in the research process in order to avoid rethinking the use of materials later on, or even costly recalls in the application phase. Lastly, in including the voice of "science" on panels, special care should be taken to remember that scientists, even within individual disciplines, do not speak with one voice, and, thus, individuals from a wide variety of backgrounds and disciplines should be included in such forums.

V. CONCLUSION

The researchers involved in nanotechnology are not incorrect in portraying it as "the wave of the future." Indeed, nanomaterials have many promising applications, from biomedical to environmental, that are already racing through the research and development phases, and will move quickly onto the consumer market. However, as noted by the scientists working on the nano-scale, there are still many gaps in our knowledge of the risks associated with the use of engineered nanomaterials. Given the mounting evidence for the toxicity of certain nanomaterials, in addition to the fact that nanomaterials exhibit such a great resistance to degradation and ability to travel easily into the body and through the environment, a precautionary approach *must* be taken in order to both protect our health and safety as well as foster beneficial technologies. By taking interim risk management steps to protect workers and the environment, requiring manufacturers to test the toxicity of their products, continuing research into alternative ways to reach the goals of nanotechnology, and actively engaging the public in the decision-making process, the breadth of stakeholders involved in this promising field will be able to achieve their goals without the costly backlash of the GMO debacle, or the health disaster of asbestos. As demonstrated by Maynard and his colleagues, and as elucidated in our conversations with the thirty-nine professors and graduate students working with nanomaterials at Brown University, leading researchers in this field are committed to making nanotechnology work to the benefit of all involved. However, in making decisions in the face of uncertainty, and acknowledging the limitations of science in making these decisions at the early phases of technological development, SEI researchers in the field should be conscious of facilitating and translating core concepts and concerns among stakeholders, so that a precautionary approach to nanotechnology development can be established through meaningful democratic participation.

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