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Prototyping Nanotechnology: A Transdisciplinary Approach to Responsible Innovation

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In this paper, we outline some of the educational principles and techniques we utilize in a program called InnovationSpace at Arizona State University. The primary goal is to teach students the ethical, social, technical and design issues surrounding nanotechnology-enhanced product innovation. InnovationSpace is an education and research laboratory at Arizona State University in which we teach students how to develop products that create market value while serving real societal needs and minimizing negative impacts on the environment. Since 2006, some of the undergraduate student teams have been investigating the potential of nanotechnology from a variety of disciplinary angles and developing product design solutions to solve such problems related to renewable energy, clean water, solid waste disposal and healthcare. The InnovationSpace curriculum treats design as an especially effective interlocutor for facilitating nano-enabled product innovation because it mediates between technological capabilities and societal needs. This article describes the process InnovationSpace students follow as they explore the potential of nanotechnology in creating new products as an example of processes that others might undertake when initially confronting nanotechnology. In this way, the dilemmas faced and lessons learned by the students mirror the larger venture most non-experts undergo when dealing with nanotechnology. We found that the broadness of the field, the sub-visual nature of the technology, and the ambiguous social, environmental and economic implications of nanotechnology created uncertainties and produced challenges for the students. Yet, these obstacles were overcome through the use of a curriculum of intense research, creative exploration and transdisciplinary team work that encouraged students to carefully examine specific contexts of use. The goal-oriented, immersive, fun, fast-paced and creative educational experience made these challenges surmountable. In this paper, we describe this structured inquiry, the challenges of learning about nanotechnology and how analyzing, visualizing, and materializing nanotechnology from transdisciplinary perspectives aided in responsible innovation. As a conclusion, we offer suggestions on how to draw from the discoveries of InnovationSpace and apply them in educational programs focused on nanotechnology.

Keywords: Innovation, Scenarios, Nanotechnology, Societal Implications.

1. RESPONSIBLE INNOVATION: RECOGNIZING VALUES IN SCIENCE & TECHNOLOGY

Every object tells a story. Behind and within the technological artifacts populating our daily lives are cumulative worlds of design, politics, economics, values and science. Products emerging from nanoscale science and engineering (NSE) are no different. Today nano-enabled products are mundane—golf ball coatings, stain resistant pants, and laboratory materials—but fascinating in the stories they tell.

It is not difficult to find several stories about the potential of nanotechnology in popular literature. The first story goes something like this: nanotechnology has the potential of inspiring ground breaking innovations and generating record windfall profits in a wide variety of markets. Investments have been enormous. The ability to manipulate matter on the scale of atoms and molecules has become a targeted pursuit of the global science community. According to the National Science Foundation (NSF), 60 countries are investing heavily in NSE research and development (Roco, 2005). According to 2001 NSF estimates, the global nanotechnology industry is expected to grow to \$1 trillion by 2015 (Roco, 2001). Since then, industry white papers have put the figure at \$2.78 trillion (Global Industry Analysts, Inc., 2008).

The economic projections are accompanied by visions of greater health, equity and wellbeing arising from

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nanotechnology. In some circles, nanotechnology has become equated with progress and the next technological revolution (Fisher et al., 2008). While the technology is arguably still in its infancy, nano-based materials have found their way into a range of such consumer products as stain-resistant Brooks Brothers' ties and Eddie Bauer khaki pants, face creams, skis, more durable tennis balls, translucent sunscreen lotions and kitchen paint. Yet as Barnaby J. Feder (2006) notes in the *New York Times*: "It's a discouraging list for nanotechnology purists," adding that "the items have little to do with the society-changing breakthroughs nanotechnology champions anticipate," such as pollution prevention and cleanup, water purification, energy savings and cures for major diseases. The second story about nanotechnology is one of hope and potentiality.

Given the widespread association of nanotechnology with revolutionary and disruptive innovations, it is necessary to think carefully and systematically about the potential futures that it enables and constrains. Educational programs in engineering ethics, biology in society, and sustainability are beginning to ask some of the questions about outcomes of technological innovations. And given the potentially massive impacts of mass-produced goods, there is also a pressing need to teach responsible practices of innovation and to consider more carefully how technologies are used.

Understanding the manifold complexities that transform technological discoveries into tangible products of everyday use is critical (Toumey & Baird, 2006). In traditional engineering education, the focus is often on enhancing science and engineering knowledge towards the creation of new products. However, what is often left out is questioning what is good for society and the environment. Unfortunately, cultural, environmental and economic factors are often excluded from the teaching of engineering ethics (Berne & Schummer, 2005).

If NSE is to deliver on its promises as a catalyst for generating products and services with revolutionary and positive social benefits, the people on the front lines of product development, most notably designers, business developers and engineers, should be educated to consider their societal and environmental dimensions from the earliest stages. This is especially true for products and services that are intended to enhance human health and performance. According to science policy analysts Sarewitz and Woodhouse, "Unless present motivations for science and innovation change," nano-enabled technologies will focus on "people in affluent societies [to] cope with everything from neurosis to impotence to the asymptotic decline of our aging bodies... [with] little benefit for those who needs are greatest" (Sarewitz & Woodhouse, 2004, p. 69). There is a need to consider the ties between innovation, equity and responsibility through the specific lens of design, which focuses attention of users and the social meaning of objects (Boradkar, 2010).

The third story about nanotechnology—and perhaps technology more generally—is that innovation is a developmental process that is devoid of values, desires and ethics. However, a call to consider the social and environmental dimensions of technology indicates that there are choices made throughout the innovation process. Values-free technology is a myth. We have moved away from an old Schumpeterian sense of innovation as a cold impersonal process from invention to market (Schumpeter, 1975). Innovation is instead a messy culmination of discoveries, technologies, choices, institutions and social structures that create something anew out of uncertain conditions (Lane & Maxfield, 2005). Innovation is not just a package of novel things, but a constructive practice that manifests values, desires and notions of what is good. Designers should thus consider users (von Hippel, 1986) and their preferences, while considering the manifold social effects of a product. This includes what happens after the intended user is finished with the product. The idea of "cradle to cradle" (McDonough & Braungart, 2002) implies a responsibility to consider the life span and death as part of the calculus of a 'good' product.

These stories—of economic vigor, of boundless potential, of value-free innovation—and their correctives not only complicate everyday notions of technological innovation, but also create challenges for teaching and learning about emerging technologies like NSE. In this paper, we focus on one part of the equation by investigating the pedagogic principles and procedures used to teach nanotechnology-enabled product development. We examine at InnovationSpace, a transdisciplinary education and research laboratory at Arizona State University where we teach students how to design and develop products that create market value while serving real societal needs and minimizing impacts on the environment. In this paper, we focus on undergraduate student teams that investigate nanotechnology from a variety of disciplinary angles, articulate the socio-technical complexities and design a nanotechnology-enabled product. We describe the exploration and creation of product designs as examples of learning processes that others undertake when confronting nanotechnology for the first time. In this way, the dilemmas faced and lessons learned by the students of InnovationSpace mirror the larger challenges most non-experts face when learning about nanotechnology.

2. OVERVIEW OF INNOVATIONSPACE

Now in its seventh year, InnovationSpace guides teams of students in generating new product concepts and promotes their transfer to the marketplace (Boradkar, 2009; Shin, Boradkar & Fischer, 2008; Fischer, 2005). A group of faculty members from a variety of disciplines teach students how to identify pressing individual and societal needs and thoroughly research and analyze the technological, economic, social and environmental implications of their design solutions. The program is a joint venture among the Herberger Institute for Design and the Arts, Ira A. Fulton School of Engineering and W. P. Carey School of Business at Arizona State University. Each year, three sponsors are chosen to engage student teams in a problem space and to augment their learning with applied research. InnovationSpace has partnered with the Center for Nanotechnology in Society at Arizona State University, a National Science Foundation program that explores the societal implications of nanoscale science and engineering.

Central to the senior capstone project is transdisciplinary team-based learning. The InnovationSpace curriculum is built on the premise that a traditional discipline-specific education no longer provides enough expertise or variation in thinking to handle the complex challenges of new product development. The effort requires transdisciplinary teams in which boundaries between knowledge and perspectives are integrated. This premise is particularly relevant to nanotechnological innovation, in which new and challenging interdisciplinary activities are arising among different groups of NSE researchers, scientists and their colleagues in social science and humanist disciplines (Barben et al., 2008).

InnovationSpace teams include undergraduate students from engineering, visual communication design, industrial design and business and involve an equally diverse faculty, who deliver content in their areas of expertise relating to new product development. The students are also guided by a wide array of expert external consultants.

2.1. Curriculum

The project is completed over two semesters during the academic year through two InnovationSpace courses: *Collaborative Design and Development I* in fall semester and *Collaborative Design and Development II* in spring semester. The project is completed in seven phases: Phase 1 (Collecting Information) involves primary and secondary research into healthcare needs that might benefit from NSE-based solutions; emerging social, technological and market trends; and research in sustainable product design. In Phase 2 (Making Discoveries), student teams analyze the information collected and identify specific NSE-based solutions to pressing needs. Phase 3 (Creating Opportunities) involves the generation of a range of product ideas through brainstorming. The Preliminary Innovation Proposal, written in Phase 4 (Fall Semester Documentation and Presentation) catalogs all work done during the semester. In Phases 5 and 6 (Developing Selected Product Concepts and Finalizing Product Concepts), the students develop select product ideas with the goal of making them functional, aesthetically appropriate, well-engineered, sustainable, socially responsible and market-worthy. Phase 7 (Spring Semester Documentation and Presentation) concludes with a public presentation and exhibit of the products at ASU's Design Gallery to which corporate sponsors as well as members of the ASU academic community and local designers and business owners are invited.

Students interested in the project are invited to apply and selected based upon grades, resumes and their level of enthusiasm for the program. All students are asked to take the Myers-Briggs Type Indicator tests and review the results before assembling the teams. The test results are not necessarily used in the formation of teams, but they help increase awareness of individual differences and therefore aid in team communication. In-class team-building exercises, disciplinary knowledge-sharing assignments and project review sessions are conducted to monitor progress of each team. A graduate teaching assistant takes an active role in helping the teams maneuver through the complexity of the project over both semesters.

Over the two semesters, students engage in field research, diagramming, brainstorming sessions, expert interviews, visualization exercises, and rapid prototyping in order to help them think as creatively as possible. ASU faculty members, experts in relevant industries, scholars of sustainability and nanotechnology, social scientists, entrepreneurs, intellectual property managers and other mentors are invited to class to interact with the student teams and guide them through the process of product innovation. Each student team has dedicated studio space through the entire duration of the project. In addition, they have access to computer labs, a wood and metal model-making workshop, and a rapid prototyping facility equipped with 3-D printers, CNC routers, laser cutters and several other machine and hand tools.

2.2. Integrated Innovation

The thrust of InnovationSpace is a new model of product development known as Integrated Innovation (Boradkar & Duening, 2009; Rothstein & Wolf, 2005) which provides a road map for product development that systematically

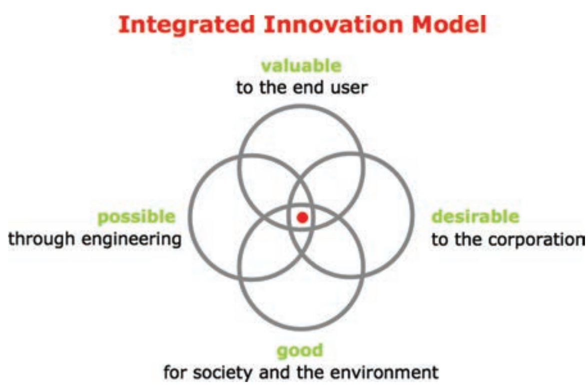

Fig. 1. The Integrated Innovation model of responsible product development.

guides students through a process in which they identify pressing social needs and thoroughly analyze the technological, economic, social and environmental implications of their design solutions.

This simple and elegant model devised by Paul Rothstein (Rothstein & Wolf, 2005) and updated by Boradkar & Duening (2009) helps product development teams build up innovative product solutions by exploring questions of what is possible through engineering, what is desirable to business, what is valuable to users, and what is good for society and the environment.

This pedagogical approach fills a critical gap in engineering, design and business education and introduces responsibility into the product development cycle. Using the model of Integrated Innovation, students aim to create products that

- Satisfy user needs and desires;
- Apply innovative but proven engineering standards;
- Create measurable value for business;
- Benefit society while minimizing impacts on the environment.

In this way, design is seen as an especially effective interlocutor for facilitating nanotechnology-enabled product innovation because it mediates between technologies and people's needs. Design plays a critical role in influencing the ways in which knowledge-based technologies are materialized in products and practices.

Critical to InnovationSpace's success is financial support and real-world mentorship from its university and business partners. To date, program partners and projects have included:
Arizona Business Accelerator: Product concepts that improve the daily lives of aging baby boomers;
Intel Corporation: Product concepts that enhance the independence and increase the comfort and safety of home environments for elders;
Herman Miller Inc.: Product concepts that improve acute-care and ambulatory-care environments for patients and healthcare providers;
Procter & Gamble: Product concepts that improve the lives of women over age 65 and people who are blind;
Center for Cognitive Ubiquitous Computing (ASU): Product concepts that expand access to printed materials for people who are blind;
Center for Nanotechnology in Society (ASU): Product concepts that enhance freedom, privacy and security for citizens and communities using the emerging field of nanotechnology;
Flexible Display Center (ASU): Product concepts that increase the safety and efficiency of emergency medical responders.

Fig. 2. InnovationSpace program partners and projects.

3. INVESTIGATING SOCIETAL IMPLICATIONS OF NANO-ENABLED PRODUCTS

In InnovationSpace, student teams often focus on design for underserved needs. The projects are developed by the faculty in conversation with the partners and sponsors who fund the program. InnovationSpace, for example, has worked with ASU's Center for Cognitive Ubiquitous Computing to expand access to printed materials for people who are blind; ASU's Flexible Display Center to increase the safety and efficiency of emergency responders; Intel Corporation to support the independence of elders in their home environments; and Major Toy to develop therapeutic toys that help children master the physical, cognitive and emotional challenges of autism. Current sponsors include Dow Corning Corporation for developing product concepts that utilize the company's materials in new healthcare applications; Herman Miller, which is interested in improving the quality of such healing environments as hospitals and outpatient locations; and CNS-ASU which has charged students with the task of developing nano-based technologies for tackling urban issues related to energy, water and waste management.

The CNS is an NSF funded center that has as its mission to "organize research through improved reflexiveness and social learning which can signal emerging problems, enable anticipatory governance, and, through improved contextual awareness, guide trajectories of NSE knowledge and innovation toward socially desirable outcomes, and away from undesirable ones" (Guston, 2005). The Center works to support "anticipatory governance" which refers to the broad based capacity to "collectively imagine, critique, and thereby shape the issues presented by emerging technologies" (Barben et al., 2008, p. 992). As practiced at the CNS, anticipatory governance relies on a three-tiered platform of foresight, engagement and integration.

Foresight refers to thinking in advance about societal values and institutional change so as to leverage the relative openness of technological systems, pathways and products before lock-in of markets, values and trajectories sets in. Engagement activities broaden deliberation and participation around emerging technologies in such a way to capture and investigate societal values. Integration refers to building into the scientific enterprise attention to the broader social context. Guston (2008) explains, integration "increases the capacity of natural scientists to understand the societal aspects of their own work, be more reflective about practices and choices within the laboratory and if necessary change their practices to align their research with public visions and values" (p. 940). InnovationSpace meets all three elements of anticipatory governance—anticipation of products vis-à-vis foresight tools like prototypes, market forecasts and engineering roadmaps; engagement with a variety of user groups with different disciplinary, professional and societal perspectives; and integration of social and natural science considerations in research and education. Thus the CNS's involvement with InnovationSpace provides a way to examine the societal implications of NSE while training students in social science concepts, technology in society scholarship, and the history of science and technology.

Fig. 3. Scio: A diagnostic device (Design and image by Chris Melanson).

The CNS has sponsored four years of InnovationSpace annual projects. Each year focuses on a particular theme—Freedom, Privacy and Security (2006–2007), Human Enhancement, Biology and Identity (2007–2008), Energy and Equity (2008–2009), and the Built Urban Environment (2010–2011). These themes are meant to reduce the scope of concern from nanotechnology writ large to a focused application of nanotechnology in a particular context. This grounding of nanotechnology provides the first parsing mechanism for the students.

The CNS is also particularly interested in products that spark ethical reflection, highlight ambiguities like dual use, or provide a glimpse into possible realities of popular nanotechnology visions. For instance, one common vision for medical nanotechnology is a device that can detect biomarkers in the blood, enabling detection of disease before symptoms. An InnovationSpace team in 2007–2008 developed a device which they called "Scio" for cancer patients in remission. Scio was designed to enable patients to draw and enter their own blood into a device equipped with the technology for detecting biomarkers of disease. The resulting data could then be transmitted wirelessly to an oncologist, who would then follow up with advice on next steps. The team was confronted with ethical issues surrounding the product, such as the role of insurance companies, who controls the biological data, and patient anxiety spawned by awareness of an imminent disease. These were dilemmas that were explored in a CNS-ASU scenarios workshop, The Future of Medical Diagnostics (Selin, 2008), a separate event from InnovationSpace, yet one that provided some triangulation of research, expert contacts, and solid source material for the students. This connection demonstrates how linkages to other university activities are actively sought to enrich the perspectives of the InnovationSpace students and their work with the CNS.

To give a sense of the range of products invented, this paper focuses on the project from 2006–2007 when the CNS teams were given the task of prototyping nanotechnology-enabled products that address issues of freedom, privacy and security. This thematic choice drew attention to the issues surrounding technological surveillance, heightened concerns over security, the legal status of biomedical data, and the security of natural resources. CNS's involvement explicitly meant to bring to the surface the social dimensions of technology—dual use, unintended consequences, wider legal contexts, etc.—to highlight the challenges of guiding innovation towards positive outcomes. The interpretation of this theme, however, was left flexible to accommodate the interests of the student teams.

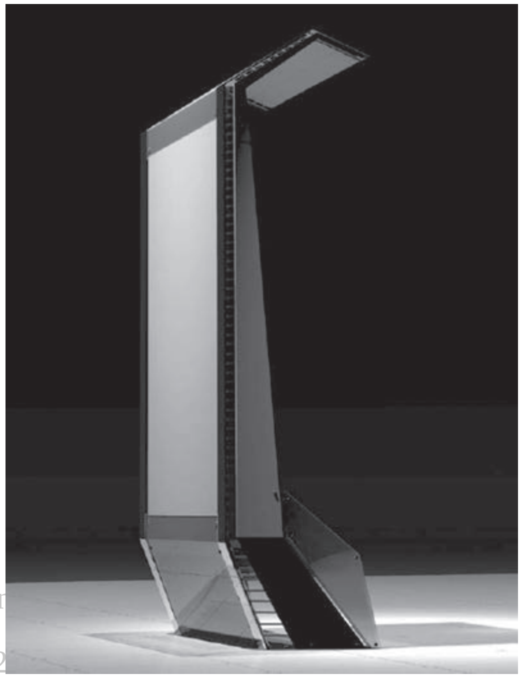

Fig. 4. Current: An energy kiosk (Design and image by Susan McKinney.

One of the teams, Speck, created a system for using human locomotion to generate electrical power. Its project called for installing nano-enabled piezoelectric floor tiles in such highly-trafficked public places as airports and shopping malls. The tiles would absorb stress from the weight and traction of passers-by and convert it to electricity. The energy is then stored in kiosks that double as recharge ports for electronic devices such as cell phones, mp3 players, and computers. These kiosks were designed as interactive educational displays for increasing public awareness of energy conservation.

Another team, Nanopants, created a personal diagnostic device for people who require frequent health monitoring. Users, for example, can drop a nanosensor the size of a fingernail into a toilet, where it analyzes the content of human waste. The data are relayed via a wireless connection to a display unit. The device also can be networked with other electronic outputs, including computers and cell phones, to alert remote caretakers, such as the children of aging parents, to potential problems. This product was meant to extend health care to places and people with limited access, thus addressing inequities in health care delivery systems thereby providing more security to consumers.

Fig. 5. Dialog: A personal health monitoring device (Design and image by Tom Filardo).

The third team, Think Small, added a bioengineering component to their final project. The team devised a scheme in which living trees are injected with a genetically modified yeast strain that causes the leaves to produce ethanol. A nano-based device filters the ethanol from the sap of the manipulated trees, what the students called "Electricitrees." Think Small estimated that nearly four gallons of ethanol could be produced each day using this method. They surmised this innovation would contribute to energy independence.

Fig. 6. A brochure promoting Electricitrees (design by Chip Davenport).

4. CHALLENGES IN PROTOTYPING NANOTECHNOLOGY

The undergraduate student teams investigate nanotechnology from a variety of disciplinary angles, articulate the socio-technical complexities and design a prototype of a nano-enabled product. As the students build up their understanding of Integrated Innovation and nanotechnology, they face several challenges. These involve understanding what nanotechnology is, confronting the ambiguous societal effects of nanotechnology, characterizing the sub-visual, building a prototype, and attesting the business proposition. However, the InnovationSpace curriculum provides highly structured methods that enable students to learn effectively and manage these challenges.

4.1. Discovering Nanotechnology

We discovered that the students had to work hard to learn about nanotechnology. A few of the students faced the problem of scientific literacy and most struggled with the conception of such a broad and futuristic field. The staggering number of research projects labeled nanotechnology, and the confusions caused by products like NanoMagic and ipod Nano, added to the confusion. Understanding nanotechnology is also complicated due to the fantastic descriptions often found in the literature (Toumey, 2006). Indeed there are expert arguments over what counts as nanotechnology that are aggravated by all of the futuristic claims associated with nanotechnology (Selin, 2007).

However, these problems of sorting out what is nanotechnology have been made somewhat simpler in recent years with more and more accessible information about nanotechnology. The Nanoscale Informal Science Education program (Glass, 2007), the Woodrow Wilson database of consumer products (Maynard & Michelson, 2006) and the variety of public outreach projects hosted by the National Nanotechnology Initiative were regularly consulted. Students also conducted expert interviews in the discovery phase and learnt about the fundamental research in nanotechnology. In some cases, "nano" became a code for any and every thing—a source of limitless possibility. In one light, this result makes sense as nanotechnology has been talked about as a general-purpose technology (Youtie et al., 2008). However, nanotechnology is not magical and the sponsors at the CNS quickly learned to ask: "What is the scientific basis for this application?" in response to the students' product proposals.

The breadth of the field is matched by the scope of potential applications. Nanotechnology-enabled applications can impact health care, or aeronautics, or fashion. Within each application there are a range of social, legal and ethical concerns. Sunscreen is a good example of a product surrounded in controversy. While nanoscale titanium dioxide is heralded as smoother and less visible, thereby improving on ease of use and aesthetics, there is concern about the safety of the particles (Nohyenek et al., 2007). While conducting research about nanoparticle safety, students were asked to study Food and Drug Administration regulations, consumer advocacy groups, chemical safety commissions and product assessments from a range of actors from L'Oreal to the activist group ETC. The risk assessment mechanisms—as well as the legal structures and patent systems—that currently govern nanotechnology safety are slow to respond and inconclusive, yet we ask the students to make judgments. The goal is to help them recognize that technological innovation can be both good and bad, contested *and* ambiguous. Design solutions have to negotiate the tensions between these polarities, and the two questions of the Integrated Innovation model "what is possible" and "what it good?" embody this tension. Students learn that getting to know nanotechnology also means being aware of its unintended consequences.

4.2. Nanotechnology and Societal Values

In 2007–2008, an InnovationSpace team produced a Societal Development and Effects Forecast illustration (see Fig. 7) which laid out different trends associated with nanotechnology's development across a number of different applications. However, this rosy picture of increased wealth and health was sometimes contrary to some of their other findings. For instance, in initial product sketches, one team intended nano-sensors to "read" an infant's emotional state and communicate that state to the parents. They decided that such a device may limit and warp the parent-child relationship and rejected the idea, yet not until a charged debate about the morality of the device. Another team became concerned about the environmental, health and safety issues around the disposal of nanoparticles in wastewater. They continued the development of the product but added in safeguards to minimize hazardous impacts. Much to the satisfaction of the CNS, students grappled with the notion of dual use—that a technology designed for one purpose could be used for a more nefarious one. For instance, Speck's piezo-electric tiles were imagined used as a source of energy generation in a shopping mall, but could also be considered as a tool of surveillance, by authorities or marketing factions.

These questions of what is good for society and the environment required careful analysis, sustained dialogue, and group judgment. In many ways, design structures the use of an object. The form of an object and its embedded prescriptions for use can serve to reduce or eliminate ambiguity. Thus the students were challenged to devise ways to limit misuse through industrial design as well as through other tools like licensing agreements. The moral dilemmas around diagnosing a disease without a cure that arose in the case of the presymptomatic diagnostic, were eased by tailoring the device for use by cancer patients checking for re-occurrence. In this way, the students got to grapple with the notion of values informing technologies and how social outcomes can be considered in advance of commercialization and adoption. The absorption of such social science ideas—dual use, unintended consequences, equity—were learning objectives of the CNS that meshed nicely with the learning objectives of InnovationSpace.

4.3. Visualizing the Sub-Visual

A third challenge for the CNS sponsored students of InnovationSpace in prototyping nanotechnology is the problem of visualization. Nanotechnology is not human scale. Talking about 1/80,000th of a human hair hardly helps. Gimzewski & Vesna (2004) note that attempting to visualize the scale of nanotechnology causes our mind to "short circuit," with the nanoscale nearly impossible to intuitively grasp, on a scale "too abstract in relation to the human experience." While the students may "see" images of nanotechnology, it is a stretch to help them to understand that what they are seeing has been sliced, enhanced and colored—and might altogether be a model rather than a physical thing.[a]

The process of visualizing design generally includes sketching, virtual modeling and physical modelmaking. Illustrations were developed to help simulate the effects and operations on the nanoscale. Figure 8 is a heuristic from the Innovation Proposal developed by team

[a]The Scanning Tunneling Microscope has a sensing tip that differentiates densities (conductivity) in materials.

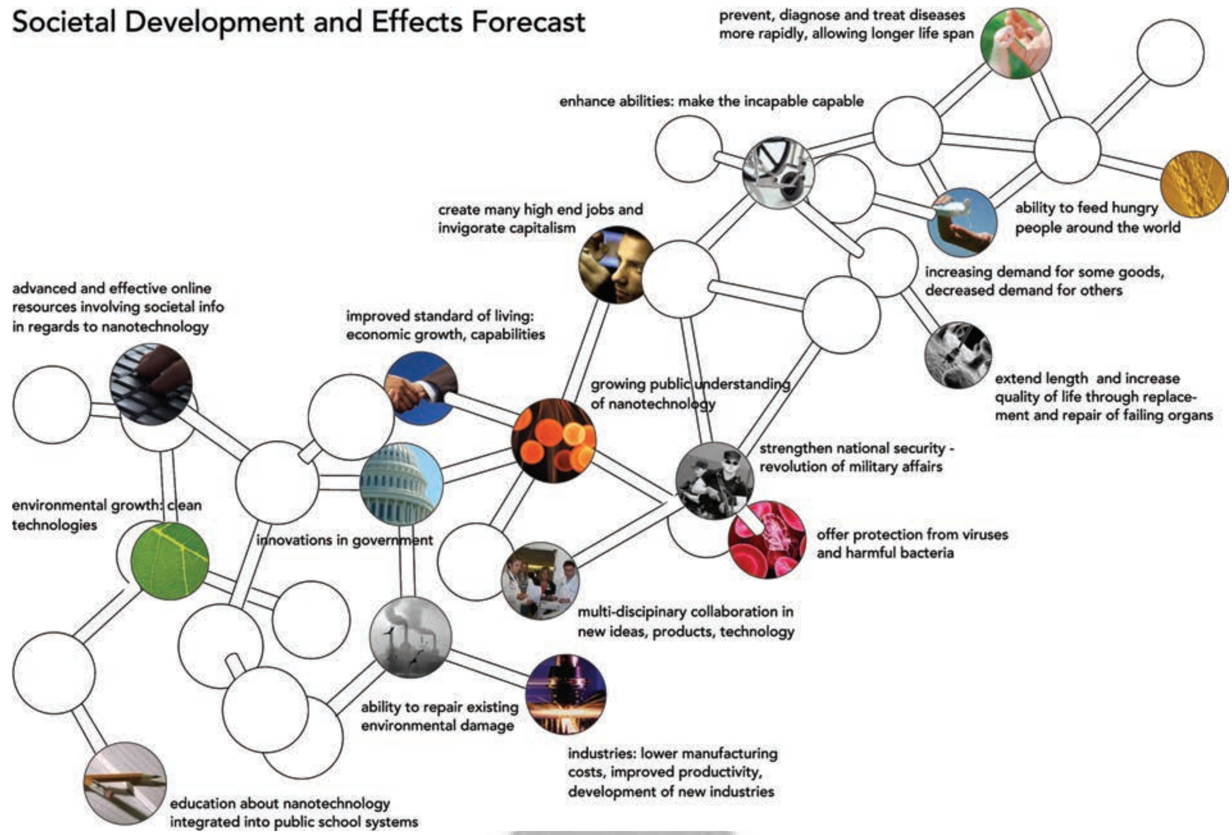

Fig. 7. A diagram showing societal development and effects (image by Julie Lovegrove).

Nanopants to communicate differences in scale. With a slogan "Power to the People," team Speck evoked energy and nanowires as can been seen in Figure 9. To "build" their product, they rigged a light bulb to realistically sized tiles such that it lit up with the pressure of footsteps. Through the use of large scale prototypes, the students exhibited microfluidic circuitry and processes of photosynthesis from models. While sketches and computer renderings provide a reasonable representation of design solutions, physical models offer the best means of judging tactile qualities, aesthetics and the scale of the product.

4.4. Building Nanotechnology

The students also face the challenge of building prototypes for the nanotechnology-enhanced products they design. Since it is not possible for them actually build a nanotechnology-enabled product, they have to think of creative ways with which to materially demonstrate the subvisual concepts. It is not enough to say "nano inside"—rather there must be some displays, figures, models or structures that relay the workings of nanotechnology. Product sketches and renderings are often the first step in visualizing these products (see Fig. 10).

Early in the design process, when ergonomic issues and overall decisions of form are being figured out, designers generally create models from soft materials such as expanded polystyrene (EPS) foam (trade name Styrofoam), rigid polyurethane foam (PU), basswood, styling clay, etc. These models—often referred to as white models, gray models, conceptual models or form studies—are unfinished and unpainted, and are generally used internally by the product development team to make design decisions (see Fig. 11). These models offer some sense for what the final product could look like, and aid designers in evaluating the design language, aesthetic direction, ergonomic fit, physical articulation of components and scale.

At this stage a preliminary 3D virtual model (Figs. 12 and 13) are created using such software as Rhino, Solidworks, Alias, etc. These models can be animated, exploded or manipulated in multiple ways to make visual as well as engineering decisions. These models can also be rendered in several colors, materials and textures to allow designers to make formal decisions.

3D virtual models offer the added benefit of being able to be used in with '3D printers' or rapid prototyping machines, which can create physical models from computer files using such technologies as fused deposition modeling, laser sintering, etc. As the designers add more detail to the product further along in the development process, the models improve in resolution.

For the InnovationSpace students, once the design has been finalized, appearance models—which look like the manufactured product—are created using a variety of

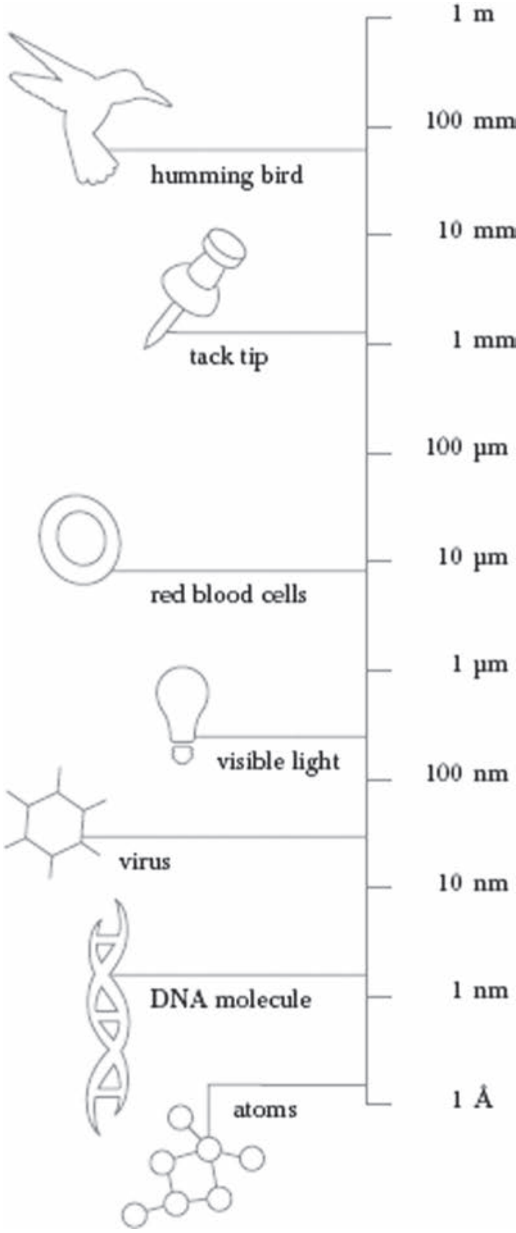

Fig. 8. A diagram showing scale variation (image by Raquel Raney).

Fig. 9. A graphic for the slogan "Power to the People" (image by Matthew Thibault).

materials and techniques. These appearance models are not functional but they are used in presentations and for user testing. In some cases, articulating parts such as hinges, latches and buttons are built to allow product development professionals and potential users to perform tactile and visual inspections of the model. Though laborious and expensive to make, appearance models provide the most accurate means by which to create material scenarios of design solutions. As all that is designed appears in the market in the future, a model is a highly reliable and tangible means by which to visualize a future product use scenario. The appearance model generally is the final physical output for a product designer, just as the functional prototype is the final physical engineering output for the engineer.

In case of high-tech product concepts (such as nanotechnology-enabled products), the building of a functional prototype requires significant financial investment and time. In such situations, simulation prototypes can be built instead. These types of prototypes can demonstrate select features and functions of the final prototype by using alternative technologies. Simulation prototypes can serve well for conceptual products that are designed around technologies that may still be in development. They cannot assist designers and engineers in making assessments of

Fig. 10. A form study model for the product Explore (design and image by William Atwood).

Fig. 11. Sketches and digital renderings for the product Explore (design and image by William Atwood).

Fig. 13. A computer generated model for the product Explore (design and image by William Atwood).

technological feasibility but can help demonstrate the type of impact the product is likely to have when manufactured.

Students in InnovationSpace are trained to build all of these models (form studies, 3D virtual models, appearance models, functional prototypes and simulation prototypes) at various stages in the product development process as a means of creating tangible, material, user-centered future scenarios of their designs. Images of these models are often used in generating user experience storyboards—visual depictions of how target populations will interact and use the goods once they are available on the market. Such modeling exercises are central in the design process to help students generate foresight on how their designs will influence people in their everyday lives. These exercises not only help them visualize their solutions in user space, but also train them in being able to evaluate the model-based scenarios, and develop tools by which to modify their designs rapidly and repeatedly in response to flaws and limitations.

Fig. 12. A computer generated exploded view for the product Explore (image by William Atwood).

In the educational context of InnovationSpace, constructing a prototype is the only viable way to "make real" nanotechnology. Through CNS's involvement, the value of prototypes in concretizing imagination and speculation with more tangible representations of the future has become clear. The prototype acts as an embodied scenario, harnessing the value of foresight methodologies like scenario development (Sharpe & van der Heijden, 2008) to appreciate uncertainties. Many of the same dilemmas unearthed in an extensive scenario building exercise that included expert interviews, desk research, a 2 day workshop, and in-depth analysis (Selin, 2008), were revealed in students' attempts to build and story board Scio. The power of building objects from the future to explore ethical dilemmas and unintended implications lies with the focus on the user experience and unraveling the variety of different ways an artifact can be realized. Much like Berne & Schummer (2005) discovered through using science fiction film and literature to make evident the ethical jams with nanotechnology, prototypes as future artifacts offer an instructional model to investigate plausible futures.

Putting a product in full-scale production is not part of the scheme; however, students were pressed to work out some of the details of mass production of the products and design them to be manufactured on a large scale. Invention disclosure forms are filed with the university's technology transfer office. One student team, who designed a personal transport scooter, has advanced their collaboration further and are working to take their product to market. The seriousness with which the student teams approach the prototype, coupled with the rigor of the

InnovationSpace "Integrated Innovation" curriculum, provide a life-like glimpse of the multivariate challenges of working with transforming emerging technologies into real world products.

4.5. Risky Business

The final learning curve that the students faced dealt with the generation of business models for the product. Not only are the teams expected to prototype a nanotechnology-enabled product, they also must outline company formation, intellectual property rights, marketing schemes, investment strategies and financial plans. However—particularly when we began this project in 2006—there were few examples of nanotechnology companies with accessible financial information in the consumer products industry. There was little market data. While there are some market research companies, such as Lux Research (Bunger, 2008), much of their data is proprietary. Without company benchmarks, it was difficult for the teams to work up full business proposals.

Perhaps due to the risk calculations that could be drafted, the most common business model follows, a biotech entrepreneurial firm, though companies were sometimes imagined as university spin-offs. Whereas company formation was more a matter of preference, the economics of the business were meant to be strictly outlined. Yet, how much a future technology will cost is a problem that confounds the best of economists. This challenge was mostly modeled and simulated rather than factually researched. That is, the teams formulated the costs of materials and created financials based on historic data and extrapolated forward. The teams used logic and speculation to profile emerging consumer markets and used analogous firms to create marketing plans. Without concrete data, the students were forced to seek their own balance between data and imagination. The main requirements from the CNS involved developing a sound argument with reasonable evidence.

5. LEARNING FROM THE FUTURE

These challenges are interesting for their real-world applicability. The students were forced to consider regulation and ethical issues in advance of facts; calculate profitability ahead of scalable production; and devise ways to explain nanotechnology to their consumers. Researchers, regulators and managers regularly face these tasks and the trials and tribulations of the students provide a learning moment for those outside of student life.

The CNS sponsored InnovationSpace as part of their program on Anticipation and Deliberation that takes seriously the need for various publics and professional groups to think through the societal implications of emerging nanotechnologies. The CNS and InnovationSpace partnership provides researchers at CNS another opportunity to work with students, but also offers a source of empirical data as to how disciplinary perspectives come to bear on emerging techno-science. InnovationSpace students wrestle with the role of technology in society and create visual, simulated and well-articulated manifestations of particular instances of nanotechnology. The students grapple with the limits of prediction and the problems with speculation. Students were worried about the open-endedness and the relevance of designing products for a distant future. Some students lamented that fact that nanotechnology wasn't "real" enough. Questioning predictions and their basis was something that the CNS hoped the students would learn as part of an education in the human and social dimensions of technology.

Nanotechnology provided a launch pad from which the students learned not only about new product development but also the about the role of technology in society. The Integrated Innovation model walks students through collecting information, making discoveries, creating opportunities and developing and exhibiting an innovation proposal for a new product. This structure served as an educational scaffolding for the students, so that they did not have to tackle nanotechnology all at once, but rather in pieces, e.g. to consider users, then observe the users and only then arriving at some product opportunity gaps. In this incremental fashion, they were provided grounded and specific ways to learn about how technologies are designed and used and with what consequences.

There are several reasons why InnovationSpace creates a meaningful learning experience, offering principles that could be emulated. Each year a lengthy evaluation of the program is conducted.[b] Without pursuing pedagogy in detail, a few key points are worth making in relation to learning about nanotechnology. These immersive group experiences with getting to know nanotechnology takes learning as a *co-creative* enterprise—not a one-way communication. This style is supported by the lessons from public understanding of science (see Irwin & Michael, 2003), that laypeople assimilate, accommodate and *make sense* of new technologies based on their own frames of reference—not just by blindly accepting information from experts in a one-way process. This *in-situ*, dialogic learning also is one with a *stake*, a stake that is communally shared. The InnovationSpace project becomes the students' final, senior capstone experience and has more in common with an internship than a classroom assignment. The fast-pace course requires that students master a new topic quickly, because the lessons learned and discoveries made have *immediate application*. A reason for knowing

[b]The evaluation of student learning for the InnovationSpace program, as distinct from CNS, is based upon a study sponsored by the National Science Foundation and conducted by the National Research Council's Board on Testing and Assessment (BOTA). The BOTA protocol assesses student learning based on three criteria: cognition, observation and interpretation.

is clearly tied to each lesson. The students have a goal—a goal that is fun, emotive, challenging, and creative, and one that applies all the knowledge they have accumulated over the year.

InnovationSpace is an effective learning experience due to the ways the information is acquired, presented and applied in a variety of different mediums, venues and through a number of perspectives. Students have different learning styles and disciplinary commitments. In each curricular phase, there are different methods for reconciling values, documenting possibilities and narrowing the focus of concern. Each method provides a window for looking at the problem, thus enabling learning through activating different ways of knowing. InnovationSpace makes use of the old adage "Show, Don't Tell" and exposes students to learning by listening, seeking, doing and making.

These features of InnovationSpace provide guidance for other programs that seek to create learning experiences about nanotechnology. Unraveling the stories underlying nanotechnology and building prototypes is a means to articulate the socio-technical complexities of nanotechnology and teach about the ethics of responsible innovation.

NSE can be considered a post-normal science, which suggests that facts are uncertain, values are in dispute and the stakes are high (Funtowicz & Ravetz, 1993). Innovation is not straightforward, value-free, or automatic. Nanotechnology is uncertain in terms of the true potential of the technology on the one hand, and the social implications on the other. In the field of design, uncertainty is practically reduced in the innovation process by building prototypes, concretizing users and environmental effects, and through speculating on business models and markets. Together, these activities provide a thorough technology assessment and enable student learning about the value of transdisciplinary teamwork and socially responsible innovation.

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