Nanotechnology

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A SENCER BACKGROUNDER DRAFT FOR DISCUSSION AT SSI 2003

July, 2003

Partial support for this work was provided by the National Science Foundation's Course, Curriculum and Laboratory Improvement Program under grant DUE-0088753.
Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation or the Association of American Colleges and Universities.

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Nanotechnology

1. Introduction

If one were to ask at random people to identify the most pressing present and future global challenges with potential technological fixes, the list might include cheap and clean energy, increased demand for potable water, reduced environmental pollution, near-term expiration of Moore's Law of computing power (an impending crisis for Silicon Valley, anyway), world hunger, national security, and cures for diseases such as cancer. Ask those same people what nanotechnology is and you're likely to get one of two responses: "Huh?" (by far the most common) or "I think it has something to do with tiny little machines that… uh…swim through your body and fix things?" (Foresight and Governance Project 2003) This is likely to change in the next couple of years, because only one field of technical research promises to develop solutions for *all* the aforementioned challenges. That field is nanotechnology.

Emergent technologies often attract the attention of both hypesters and fear-mongers. For example, genetically modified (GM) foods are both hailed as the solution to world hunger and assailed as destroyers of the natural order. Depending on your perspective, gene therapies will either cure intractable hereditary diseases such as hemophilia and Huntington's disease or will allow modern Dr. Frankensteins to create a new race of superhumans. Nanotechnology is no different in this regard than its predecessors; it will either end material need or end the reign of humanity on Earth. Given this potential impact on society, and the growing public debate over nanotechnology's benefits and risks, both science and non-science majors alike should have at least a passing understanding of what nanotechnology is. This young field can also serve as an illustrative example of how society grapples with any emergent technology, including those yet to come.

The "nano" in nanotechnology comes from the Greek word *nanos*, which means dwarf. Scientists use this prefix to indicate 10^{-9} or one-billionth. Thus a nanosecond is one-billionth of one second; a nanometer is one-billionth of one meter, *etc.* Objects that can be classified as having something to do with nanotechnology are larger than atoms but much smaller than we can perceive directly with our senses. One way to look at this size scale is that one nanometer (nm) is about 100,000 times smaller than the diameter of a single human hair. The following figure may also help to put this size scale in context. Why a particular size scale should be the basis for so much federal funding, research activity and media attention will become apparent soon.

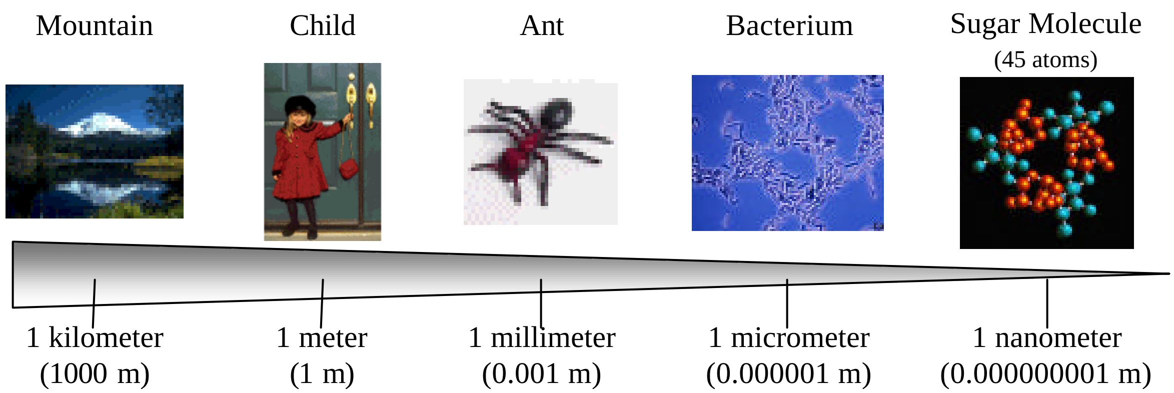

Figure 1 Objects of approximate size from 10^3 m to 10^{-9}m.

It isn't too surprising that nanotechnology is not yet a household word given that it has only been around in the research lab for the last 10-15 years. The concept of controlling matter at the atomic level—which is at the heart of nanotechnology's promise—was first publicly articulated in 1959 by physicist Richard Feynman in a speech given at Caltech entitled, "There's Plenty of Room at the Bottom," (Feynman 1959). While the term "nanotechnology" was coined in 1974 by Japanese researcher Norio Taniguchi to refer to engineering at length scales less than a micrometer, futurist K. Eric Drexler is widely credited with popularizing the term in the mainstream. In his 1986 book, "Engines of Creation," Drexler envisioned a world in which tiny machines or "assemblers" are able to build other structures with exquisite precision by physically manipulating individual atoms. (Drexler 1986) If such control were technically achievable, then atom-by-atom construction of larger objects would be a whole new way of making materials and could have the capacity to usher in a second Industrial Revolution with even more profound societal impacts than the first one.

Until recently, nanotechnology remained the province of futurists and visionaries because researchers lacked even rudimentary tools to observe and manipulate individual atoms. This changed in the early 1980's with the invention by IBM researchers of a new tool called scanning tunneling microscopy (STM) that allowed one not only to see individual atoms but to push them around, albeit painstakingly. The potential value and importance of this new tool were immediately recognized and earned its inventors the 1986 Nobel Prize in Physics. This technique and others that followed shortly thereafter allowed nanotechnology to move forward at a greatly accelerated pace. Within a few years, the field had built up enough momentum to attract the Federal Government's attention.

In 2000, President Clinton chose Caltech—the site of the historic Feynman speech—as the venue to announce the creation of the National Nanotechnology Initiative (NNI), a coordinated Federal program to fund nanotechnology research and development:

> "My budget supports a major new National Nanotechnology Initiative, worth $500 million. … the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight -- shrinking all the information housed at the Library of Congress into a device the size of a sugar cube -- detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government." (President William J. Clinton January 20, 2000 2000)

The creation and generous funding of the NNI signaled a serious and long-term commitment by the Federal Government to this new area of discovery. This commitment continues in the new administration: President Bush's FY 2004 budget request funds the NNI at a whopping $847 million. The Federal Government justifies this massive investment by pointing toward the positive benefits society will reap through nanotechnology. These are posited as a set of "Grand Challenges" that, if realized, "could provide major broad-based economic benefits to the United States as well as improve the quality of life for its citizens dramatically." These potential benefits include: (National Science and Technology Council July 2000)

- Containing the entire contents of the Library of Congress in a device the size of a sugar cube;
- Making materials and products from the bottom-up, that is, by building them up from atoms and molecules. Bottom-up manufacturing should require less material and create less pollution;
- Developing materials that are 10 times stronger than steel, but a fraction of the weight for making all kinds of land, sea, air and space vehicles lighter and more fuel efficient;

- Improving the computer speed and efficiency of minuscule transistors and memory chips by factors of millions making today's Pentium IIIs seem slow;
- Detecting cancerous tumors that are only a few cells in size using nanoengineered contrast agents;
- Removing the finest [ed.: *i.e.* smallest] contaminants from water and air, promoting a cleaner environment and potable water at an affordable cost; and
- Doubling the energy efficiency of solar cells.

2. A Little Bit of Science

To better understand how nanotechnology could revolutionize such diverse areas as, say, medicine and computing, we need to review a bit of fundamental physics. Two sets of theories relate to this discussion: *classical mechanics*, which governs the world of our immediate perception (apple falling from tree to hit Newton on the head) and *quantum mechanics*, which governs the world of atoms and molecules (electrons tunneling through seemingly impenetrable barriers). Given enough information about the initial position of an object and the forces acting upon it, classical mechanics allows one to determine with certainty where that object was at some time in the past and where it will be at some time in the future. This is useful because it allows one to, *e.g.*, track a baseball from the crack of the bat to where it will drop in center field or to successfully sink the eight ball with a bank shot off the side wall of a pool table (at least in theory). Quantum mechanics doesn't provide such comforting predictability but does a far better job explaining the strange behavior of atoms and molecules and allows us to make (at best) probabilistic assessments of where an electron is and what it might do if we poke it with a light probe. The classical world and the quantum world seem miles apart. However, as we move along the scale in Figure 1 from the large to the small, the classical rules eventually give way to the quantum rules. The murky, middle ground in between the two domains is the province of nanotechnology.

In this transitional regime, a material often exhibits different behavior than it does either in the bulk, where it's governed by classical mechanics, or as a single atom, where quantum mechanics dominates. Let's consider the element gold. We're familiar with gold as a shiny yellow metal that can be worked into a variety of shapes for our adornment. If you cut a piece of gold in half, each of the halves retains the properties of the whole, except that each piece has half the mass and half the volume of the original. (And even these sum to the mass and volume of the original uncut piece.) Cut each half in half again and anyone would still recognize the pieces as gold. And so on. You can keep doing this down to a certain size and then the properties of the pieces begin to change. One of these may be the apparent color of the material. When gold is nanoscopic, *i.e.* clusters of gold atoms measuring 1 nm across, the particles appear red![1] And if we change the size of the clusters just a little bit, their color changes yet again. That is only one example of a property that varies with the size of the object. Most of this variability doesn't begin to manifest until you get to the nanoscopic level. Therefore, if we can control the processes that make a nanoscopic material, then we can control the material's properties. Chemists have long been able to design materials with useful properties (*e.g.*, polymers); what's new is the unprecedented degree of control over materials at the molecular level. This may not capture the imagination as much as a tiny machine that precisely assembles materials atom by atom, but it is an extraordinarily interesting and useful phenomenon and is, ultimately, why nanotechnology is kicking up such a fuss.

3. Present and Future Applications of Nanotechnology

Nanotechnology is expected to have a significant impact on just about every sector of the economy through the use of nanostructured materials in medicine, the production of clean energy and reduction in energy consumption, the creation of nanoscopic sensors, new materials for optics and photonics, and ultra small magnets, the development of new techniques for the fabrication of large-scale structures, the replacement of silicon-based technology for electronics and computing, and the enhancement of consumer products. A few of the many applications will be highlighted within; for a more thorough review the reader is directed to two recently published surveys of nanotechnology. (Wilson, Kannangara et al. 2002) (Ratner and Ratner 2003)

A. Consumer Products

While much of nanotechnology's potential has yet to be realized, products that incorporate nanotechnology are already in the marketplace. The Wilson Double Core™ tennis ball, the official ball of the Davis Cup tournament, has clay nanoparticles embedded in the polymer lining of its inner wall, which slows the escape of air from the

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[1] A single gold nanoparticle cannot be seen with the unaided eye but a spectrophotometer can be used to measure its "redness".

ball making it last twice as long. Nano-Care™ fabrics, sold in Eddie Bauer chinos and other clothing since November 2001, incorporate "nano-whiskers" into the fabric to make it stain-resistant to water-based liquids such as coffee and wine. PPG Industries produces SunClean™ self cleaning glass, which harnesses the sun's energy to break down dirt and spreads water smoothly over the surface to rinse the dirt away without beading or streaking. Various sunscreens (Wild Child, Wet Dreams and Bare Zone) incorporate ZinClear™, a transparent suspension of nanoscopic zinc oxide particles that are too small to scatter visible light as do products containing microscopic particles. Nanotechnology has added value to these products through a variety of properties—impermeability to gas, water-repellence, and transparency—that manifest only or optimally at the nanoscale.

B. Military Applications

Nanotechnology would probably not be worth $847 million of federal funding if it only made incremental improvements in consumer products. Many of the high-impact applications are in the areas of defense/national security, medicine, and energy. In Fiscal Year 2003, the Department of Defense surpassed all other Federal agencies with a $243-million investment in nanotechnology research and development.[2] DOD is interested in using nanotechnology to advance both offensive and defensive military objectives. DOD's primary areas of interest are information acquisition, processing, storage and display (nanoelectronics); materials performance and affordability (nanomaterials); and chemical and biological warfare defense (nanosensors). The integration of several of these functionalities into a single technology is the ultimate goal of the Institute for Soldier Nanotechnologies, an interdepartmental research center established in 2002 by the U.S. Army at the Massachusetts Institute of Technology.

> "Imagine a bullet-proof jumpsuit, no thicker than spandex that monitors health, eases injuries, communicates automatically, and maybe even lends superhuman abilities. It's a long-range vision for how technology can make soldiers less vulnerable to enemy and environmental threats." [Institute for Soldier Nanotechnologies website]

The ultimate objective of this 5-year, $50-million effort is to create a battlesuit that better protects the soldier in the battlefield.

[2] The National Science Foundation, which funds research of a more fundamental nature, was a close second with $221million. In Fiscal Year 2004, the NSF has requested $247 million to DOD's $222 million.

C. Medical Applications

Notwithstanding the fact that no one has yet invented a little machine that will swim through your body and mechanically strip away plaque from your inner arterial walls, nanotechnology is poised to have an enormous impact on the diagnosis and treatment of disease. Recall that one of the Grand Challenges of the NNI is the ability to detect cancerous tumors that are only a few cells in size. Medical imaging could be vastly improved by using nanoparticle-based materials to enhance the optical contrast between healthy tissue and diseased tissue. Diabetes treatment could be improved by injecting a nanoparticle into the blood that was programmed to deliver a dose of insulin automatically upon sensing an imbalance in blood glucose level. Cancer may be treated someday soon with an injection of nanoparticles that latch onto cancerous tissue and cook it to death upon external application of a light source that poses no threat to healthy tissue.

That's the good news.

4. Controversies: The "Wow" to "Yuck" Trajectory

New developments in technology usually start out with strong public support, as the potential benefits to the economy, human health or quality of life are touted. Let us call this the "wow index". Genetic engineering promised a revolution in medical care, including the ability to cure or prevent diseases with a genetic basis such as Huntington's disease, hemophilia, cystic fibrosis and some breast cancers. Manipulation of plant genomes promised a revolution in how food is produced, by engineering crops with increased yield, nutritional content and shelf-life. At present, nanotechnology has a very high wow index. For the past decade, nanotechnologists have basked in the glow of positive public opinion. We've wowed the public with our ability to manipulate matter at the atomic level and with grand visions of how we might use this ability. The good news has given nanotechnology a strong start with extraordinary levels of focused government funding, which is starting to reap tangible benefits to society.

Any technology that promises so much change is bound to generate controversy, because with such awesome power comes the capacity to push beyond boundaries that society has deemed acceptable. Put another way, societal and ethical concerns can rapidly turn "wow" into "yuck". These concerns are often centered on fundamental moral and social perceptions of what it means to be human and what humanity's relationship should be with the natural world. The proponents of the NNI were not insensitive to the possibility that nanotechnology could push some of these buttons. In September 2000, the National Science Foundation organized a workshop on societal implications of nanotechnology. The report from this workshop incorporates the viewpoints of a diverse group of people from government, academia and industry on subjects ranging from public involvement in decision making, education of future nanotechnologists, economics, politics, medicine and national security. (Roco and Bainbridge 2001)

The debates surrounding many of the emergent technologies that preceded nanotechnology can help us predict a likely trajectory for the controversy surrounding nanotechnology. One such example is provided by the debate over GM foods. The genetic manipulation of crops grown for human consumption spawned a host of ethical concerns about the advisability of tinkering with the natural order. A perusal of anti-GM literature reveals a profound discomfort with human attempts to outsmart Mother Nature by incorporating genetic material from one species into another. The greater the difference of these species in the natural world, the more profound seems to be the anxiety over their mixing. Thus, incorporation of a cold-water fish gene into a tomato to increase the fruit's resistance to frost damage is higher on the "yuck index" than incorporation of genetic material from one species of plant into another. The public backlash against GM foods, which detractors labeled "Frankenfoods", crippled the industry and ultimately cost billions in lost future revenues. In a sense, this industry went from "wow" to "yuck" to nearly "bankrupt".

Nanotechnology's "yuck index" is rising in part because of the recent publication of Michael Crichton's novel *Prey*. (Crichton 2002) The author of *Jurassic Park* (Crichton 1990) and other techno-horror stories describes a chilling scenario in which swarms of nano-robots—equipped with memory, solar power generators, and powerful software—begin preying on living creatures and reproducing. Like the fictive dinosaurs, the nanobots surprise and overwhelm their creators when they rapidly evolve beyond the scientists' capacity to predict or control them. Or, in the words of *Prey*'s protagonist, "Things never turn out the way you think they will." In the introduction to the book

Crichton credits Eric Drexler's "gray goo" scenario with inspiring the premise of his story. In brief, the gray goo scenario is the destruction of humankind by "omnivorous" nanomachines that "spread like blowing pollen, replicate swiftly, and reduce the biosphere to dust in a matter of days." (Drexler 1986) This fear was echoed more recently in an influential essay entitled, "Why the future doesn't need us," in which Sun Microsystems CEO Bill Joy warns that the confluence of nanotechnology, artificial intelligence, and biotechnology could pose a mortal threat to humanity.

Such writings have drawn the attention of a small but vocal activist organization known as the ETC Group: the Action Group on Erosion, Technology and Concentration. (ETC Group) Formerly known as the Rural Advancement Foundation International, the ETC group

> "is dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights. To this end, ETC group supports socially responsible developments of technologies useful to the poor and marginalized and it addresses international governance issues and corporate power." [ETC group website]

Its technology interests include biotechnology, biological warfare and human genomics with a special emphasis on genetically modified organisms such as the so-called Terminator seed. This Monsanto product is engineered to produce sterile plants, thus ensuring yearly repeat sales to farmers who would otherwise harvest the fertile seeds for subsequent plantings. ETC group's interest in nanotechnology dates back to early 2001 with the publication of a report that lays out the perils of advancing technologies such as biotech and nanotech. The objections of this group to emerging technologies seem to be based less in concerns about technology gone awry, *i.e.*, the gray goo scenario, than in the technologies' capacity to increase the gap between rich and poor, and developed and developing nations, through control over the means of production and distribution of the technologies. (Mooney 2001) This type of criticism is not leveled exclusively at nanotechnology but seems broadly applicable to any new technology.

Members of the ETC group are not the only ones whose criticism of nanotechnology is more social than technical. Gregor Wolbring, a research scientist at the Department of Biochemistry and Molecular Biology at the University of Alberta, founder of the International Network on Bioethics and Disability and self-proclaimed "thalidomider", critiques technologies that aim to enhance human performance or remediate or prevent disabilities. He envisions a scenario in which nanotechnology could be used not only to further marginalize the disabled but to coerce the healthy into improving themselves and their offspring. (Wolbring 2002) This outcome could be dubbed the "nano-GATTACA" scenario, after the 1997 film GATTACA,[3] which is set in a future where genetic engineering allows all children to be born with physical and mental enhancements. In the film, a two-tier society results in which the genetically enhanced oppress those people whose rebellious parents have chosen to produce them the "natural" way. Michael Mehta, a sociology professor at the University of Saskatchewan, is concerned about the failure of the "triple helix" of State, university and industry to include the fourth helix, the public, when making decisions about the regulation of emergent technologies such as nanotechnology and biotechnology. (Mehta in press) Mehta is also concerned about the prospect of "nano-panopticism" or a world in which all citizens are subject to gross invasions of privacy through the misuse of nanoscopic surveillance technology, increased computing power and storage, and lab-on-a-nanochip technology for acquiring genetic information without knowledge or consent.[4]

Not all potential impacts of nanotechnology will be social in nature. The technology is, after all, based on the production and use of materials. As such, issues of environmental and toxicological effects must also be addressed. History is replete with examples of technologies or materials that were enthusiastically embraced by society, and then found years later to cause environmental contamination or disease. The chemical DDT killed disease-bearing mosquitoes, thus allowing areas with tropical and sub-tropical climates to be more safely populated and developed, yet was ultimately banned in the US after it was linked to destruction of animal life. CFC-based refrigerants allowed for affordable air-conditioning, yet were ultimately banned after they were linked to destruction of the ozone hole. Asbestos was used as a fire-retardant and insulator in many buildings until it was found to cause a deadly lung disease. Some materials, such as semiconductors, are not in themselves known to be harmful but are produced though environmentally burdensome processes.

[3] The name of the fictive Gattaca corporation, the primary setting of the film, is composed solely of letters used to label the nucleotide bases of DNA: guanine, adenine, cytosine and thymine.
[4] This is also reminiscent of a scene in GATTACA, in which a woman surreptitiously gathers skin cells sloughed off by her lover for genetic analysis to determine whether he would be a good mate.

Nanotechnology has tremendous potential to improve human health and the environment; however, it could also have unintended impacts. Nanoparticles' ability to penetrate into living cells could be exploited to produce a new drug, or it could result in toxicity. Nanomaterials could be used to produce cheap and energy efficient filters that improve drinking water quality, or they could become environmental contaminants. Given the breadth of materials and devices that fall under the broad umbrella of nanotechnology, all of these outcomes may result to one extent or another. Despite the massive amount of money that supports nanotechnology research and development, *i.e.*, the development of new *applications*, little research has been done on potential *implications*.

5. SENCER Concepts

Nanotechnology lends itself well to the SENCER model: it is inherently interdisciplinary, touching upon just about every field of science and engineering, and provides many points of entry for students in non-technical fields, who will find plenty of opportunities to debate its social, ethical, legal and economic impacts. Many parallels can be drawn between nanotechnology and other complex technical issues such as biotechnology and genetic research, thus further broadening and enriching the discussions. Finally, nanotechnology is now. Thus there is an opportunity to equip students with the background and perspectives that will prove useful as they track the trajectory of nanotechnology into the future.

6. Acknowledgements

The author wishes to acknowledge Prof. Vicki Colvin, Dr. Kevin Ausman, Rice University, and the Center for Biological and Environmental Nanotechnology. This work was partially supported by Nanoscale Science and Engineering Initiative of the National Science Foundation under NSF Award Number EEC-0118007.

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