Project Number: WGM-IO05

# NANOTECHNOLOGY: FUTURE & IMPLICATIONS

An Interactive Qualifying Project Report

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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Date: May 6, 2004

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## *Abstract*

Nanotechnology, now becoming a "buzz" word, promises novel materials with unique properties, faster and cheaper computers, and new medicines. Advocates of molecular nanotechnology believe manufacturing will be revolutionized: items will one day be assembled atom by atom by molecular assemblers. The risks, concerns and implications of such technologies are considered. The opinions of scientists in the field were incorporated in an effort to separate the fact from science fiction and develop a more realistic conjecture of the future.

**Wheels must turn steadily, but cannot turn untended. There must be men to tend them, men as steady as the wheels upon their axles, sane men, obedient men, stable in contentment.**

**Aldous Huxley**
***Brave New World*, 1932**

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# CHAPTER I: INTRODUCTION

The subject of this IQP is the emerging field of nanotechnology. Since nanotechnology is in its infancy, it would seem that now is the ideal time to conduct an IQP with the goal of forecasting the development of the technology. In addition, now is the ideal time to question the assumption that advancement of this technology will necessarily equate with societal progress. This project, therefore, is a combination of a Science, Technology, and Society (S.T.S.) project and a Technological Forecasting project.

This project seeks to investigate the current state of the art of nanotechnology and probe its future. An emphasis will be placed on the breadth of this interdisciplinary field. A literature review has revealed a number of controversies surrounding nanotechnology. Within the scientific community, for example, there is a controversy over the feasibility of the eventual realization of molecular nanotechnology (the manufacture of objects with molecular precision). Additionally, between the proponents and dissenters of nanotechnology, there is a controversy over whether nanotechnology will usher in a new utopian era or open a metaphorical Pandora's Box, unleashing untold nano-evils on humanity. These controversies in particular are to be explored by investigating the opinions of individuals working in the field of nanotechnology. If nothing else, this project seeks to provoke those individuals to consider the unintended consequences of their work.

The intended audience of this IQP is the scientific community and the public at large. Ideally, the conclusions drawn in this IQP would shape the direction that nanotechnology develops. Everyone who reads this IQP should be inspired to participate in the responsible development of nanotechnology with the good of humanity in mind. Realistically, the conclusions of this IQP will only prepare its readers for the future inevitable development of nanotechnology by suggesting some possible directions that the technology might develop and some of the possible implications of that development.

**Literature Review**

A literature review has revealed controversies of interest to explore. The details of these controversies are to be investigated through interviews conducted with individuals working or interested in nanoscience and technology. A list of questions has been developed that will, first, define the field of nanotechnology of interest to the interviewee, and then probe their thoughts on the future. If the individual does not respond at length to a particular question, for example, “Do you have any concerns about the future of nanotechnology?”, they will be prompted to respond to some of the findings from the literature review, in this case, that Nick Bostrom, of the Faculty of Philosophy at Oxford University, ranks “deliberate misuse of nanotechnology” as the greatest existential risk to humanity (Bostrom).

There has been one previous IQP relating to nanotechnology, titled “Nanocomputers: Technology, Design & Implications.” Prepared by Mary Devlin and Brendan Smith in 1999, this IQP, as the title suggests, focuses on nanocomputing and nanoelectronics. This IQP seeks to explore and emphasize the breadth of nanotechnology in order to justify the supposition that it will have vast and widespread impact on the future.

## Methodology

An investigation of the possibilities and implications of nanotechnology falls under a number of the broad descriptions of the IQP. This project not only seeks to forecast the future, but also to examine some of the implications that the emerging science and technology may have on society. For example, if there is consensus that molecular assemblers will one day become reality, what effect may that have on society?

The literature review has led to the formulation of the following set of questions, designed to investigate the hopes and concerns of the interviewee about nanotechnology and the future of humanity.

1. Since nanotechnology is such a broad field, how do you define it in terms of your own interests? What is your working definition of nanotechnology?
2. In your opinion, what nanotechnologies are the most important right now? Why?
3. What new nanotechnologies do you believe are closest to commercial fruition?
4. What technologies would you like to see emerge? Why?
5. Where do you see the most potential (for growth, for societal change, for financial gain) for the future?
6. What impact will nanotechnology have on society in the future?
7. What sorts of benefits do you expect to come from advancing nanotechnologies?
8. Do you have any concerns about the future of nanotechnology?

The first two questions are designed to give a frame of reference for each interviewee with regard to which discipline of nanoscience they have the greatest interest. The third question is designed to gradually ease the interview into a discussion of the future of society and nanotechnology, by asking about the immediate future. Questions four, five and six are meant to reveal opinions on the more distant future, and the possibilities that nanotechnology may eventually realize. Questions seven and eight further explore the idea of question six, specifically separating benefits and concerns. These questions are necessary because it is probable that the ambiguity of question six (using the neutral word "impact") will elicit a response either entirely positive or negative.

The target group for the interview/survey is scientists working or interested in the field of nanotechnology. Data collected from the interviews will be used in an attempt to characterize the thoughts and opinions of the scientific community on nanotechnology and its potential impact on the future. For example, if responses to the "concerns about the future" question are sparse, then it would seem that the scientific community truly does not let things like ethics interfere with their work. The survey may reveal the scientific community to be optimistic rather than cautiously pensive. It is also possible that responses can be used to formulate a risk analysis of nanotechnologies, if there seems to be consensus on a particular concern for the future. It should also be possible to forecast the growth of nanotechnology according to the responses about the technologies nearest to commercial fruition and those with the greatest potential. The end result should be a cohesive proposal of the possibilities and implications of the future of nanotechnology.

## CHAPTER II: HISTORY

According to many, nanotechnology found its origin in 1959, when Richard Feynman gave his historic talk, "There's Plenty of Room at the Bottom," at the annual meeting of the American Physical Society at the California Institute of Technology. Many of the ideas presented that day by Feynman were elaborated upon by K. Eric Drexler in *Engines of Creation*. Drexler later added to his legacy as a pioneering theorist in the field with *Nanosytems: Molecular Machinery, Manufacturing, and Computation*.

**"There's Plenty of Room at the Bottom"**

Feynman began his historic talk with a discussion of the possibility of writing the entire volume of the Encyclopedia Brittanica on the head of a pin. The mathematics of the miniaturization would allow each letter to be the size of several thousand metal atoms. In a bit of a parlor trick, IBM has since written the letters "IBM" on a nickel surface with 35 xenon atoms (Eigler). The procedure was done using a scanning tunneling microscope at four degrees Kelvin in a high vacuum, rather inaccessible conditions to the common man, but it did demonstrate the reality of Feynman's vision.

Feynman continued his prophetic presentation with a discussion of biology. After all, if DNA can store the information that it does, shouldn't there be analogous ways for us to store information on a similar scale? Furthermore, if cells can act as miniature factories as they do, shouldn't it be possible to build factories at the cellular scale?

The intention of "There's Plenty of Room at the Bottom," as Feynman described it, was "to show that there is *plenty* of room" (Feynman) at the bottom. He made a number of surprisingly accurate predictions for the future, given the date of his talk, including that of the miniaturization of the computer:

> Computing machines are very large; they fill rooms… But there is plenty of room to make them smaller. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. (Feynman)

Feynman's idea for miniaturization of the computer goes beyond even what we have seen today, after all, there is still *plenty* of room for further miniaturization. He said "wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across," (Feynman) goals which seem to be forthcoming.

Feynman introduced the concept of successive miniaturization as a method for reaching the nano-scale. He used as an example a lathe, used to create a new lathe at one-quarter the scale of the original. The new one-quarter scale lathe is used to build a lathe at 1/16$^{th}$ the scale of the original, and so on. He asserted that it is theoretically possible to continue all the way to the atomic scale:

> The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big. (Feynman)

The ideas presented by Feynman in 1959 have been refined, defined and debated to a great extent, but it cannot be ignored that "There is Plenty of Room at the Bottom" inspired a great deal of interest and research.

**Engines of Creation**

First published in hardcover in 1986 and now available in various electronic formats via the Internet, Eric K. Drexler's *Engines of Creation* has served as inspiration to many in the field of nanotechnology. In it, Drexler asks, "What is *possible*, what is *achievable*, and what is *desirable*?" (51) In exploring this question, he frequently refers to "foresight," that is, predicting the future. He concludes that foresight is hindered by many things, but is not impossible. Citing Leonardo da Vinci as an example, he explains how it is possible to predict future technology based on the current "foundation of knowledge" (63). This, combined with his use of biological metaphor in the first chapter (just make a machine like an enzyme!), is supposed to convince the reader of the inevitability of molecular assemblers and replicators, nanoscale machines capable of manufacturing copies of themselves as well as virtually anything else, depending on their programming. Although *Engines* reveals Drexler's proficiency at metaphor, it does not do much for proving the feasibility of the technologies that he describes. While discussing scientific principles such as exponential growth, *Engines* reads like inspired science fiction. In Chapter 7, “Engines of Healing,” Drexler presents another use for molecular machines, healing the human body by repairing damage at or below the cellular level or even selectively destroying malignancies. The potential for slowing aging to a mere trickle is even discussed. The possibilities of Drexler’s molecular machines are limitless. The scope of *Engines*, however, is limited; although the prospects of molecular machines are explored in great breadth, the ethics are hardly considered.

One of the counterarguments which Drexler chooses to respond to concerning reversible biostasis (yet another miracle of molecular machines, allowing people to be “frozen” and resuscitated at a much later date) is: “Because this sounds too good to be true” (180). Perhaps Drexler should consider whether or not it sounds too *horrible* to be true. Ethical responses to nanotechnology, like this, will be investigated later.

Nearly half way through *Engines*, Drexler refers to “fairly simple goals… transmitting heat, insulating against heat, transmitting electricity, insulating against electricity, transmitting light, reflecting light, and absorbing light” (198). Finally, there is a taste of the real rather than the fantasy. But only a taste, as Drexler rapidly digresses into a discussion of the politics that may or may not affect nanotechnology.

## CHAPTER III: THE PRESENT DAY

According to a study conducted by the World Technology Evaluation Center, advancing technology in the coming years will be characterized by “novel performance through nanostructuring” (Siegel, 4). Innovations have already occurred in the following fields: dispersions and coatings, high surface area materials, and functional nanodevices. Recent advances in these fields and the science supporting them are explored below.

The generation of nano-sized particles can be approached two different ways: a "bottom-up" or a "top-down" approach (Siegel, 15-16). The "bottom-up" approach creates powder components via aerosol techniques. The powder components can then be compacted into the final material. The second method, the "top-down" approach, begins with a suitable starting material, which is functionalized at the nano-scale. This can be accomplished in a variety of ways. Lithography, where light is used to etch a design onto a surface, is an example of this sort of an approach. The precision of lithography is limited, however, by the wavelength of light being used. "Ball-milling" is another "top-down" approach (Siegel, 16) toward nano-sized particles whereby nanostructure components are created by careful mechanical erosion of a starting material.

**Dispersions and Coatings**

Nano-sized particles in dispersions and coatings are expected to have enhanced properties. For example, a coating containing nanoparticles would have enhanced covering power, allowing for the use of less material and therefore the incorporation of expensive materials (Siegel 36).

Ceramics, cosmetics, biosensors, colorants, and abrasion-resistant polymers are a few of the technologies that could benefit from nanoparticles. Ceramics with nano-sized particles dispersed evenly throughout would have enhanced strength. Cosmetics can achieve color and light fastness through the incorporation of nano-sized particles. The flavor of low calorie foods can be enhanced with the incorporation of nano-sized flavor enhancers. Drugs dispersed at the nano-scale have the advantage of rapid delivery, even through the skin via topical creams, which traditionally have a slow delivery rate. Nano-engineered inks would have better color, resolution, drying time and permanency. Nano-engineered biosensors would be more accurate and sensitive than traditional biosensors. The high surface area of the detecting particles leads to enhanced sensitivity per unit mass.

One example of a current application of nanoparticles is in sunscreen. Zinc oxide is the active ingredient in sunscreen. Some new sunscreens use zinc oxide nanoparticles. The result is a clear cream, instead of opaque white. Because the nanoparticles of zinc oxide are smaller than the wavelength of visible light, the cream appears clear, while retaining its efficacy. ("Seeing is believing" 30) Titanium dioxide nanoparticles are similarly used in sunscreens and cosmetics, as well as a coating which makes self-cleaning glass (for information from one manufacturer, see http://www.activglass.com/). Teflon nanoparticles are used by Dockers and Ralph Lauren, among others, to make stain-resistant fabrics for clothing. A brand of antimicrobial bandage contains silver nanoparticles as the active ingredient. These are among the many ways that nanoparticles are currently finding use. ("Seeing…" 31)

**High Surface Area Materials**

Nanoparticles have a very high surface area to volume ratio. As a result, many properties are enhanced and many novel properties emerge. Small particles or clusters with a high surface area to volume ratio are already commonly used in chemistry in the form of finely dispersed metal catalysts. Porous materials with pores on the nano-scale also have a very high surface area to volume ratio. Such materials, including zeolites, are also commonly used in chemistry.

The periodic table of the elements illustrates the periodic trend in properties present in the elements. One could say that the properties of an element are determined by the location of the element in the periodic table, defined by the row and column. A third dimension, N, is also necessary to define the properties of an element, however, where N is the number of atoms in a cluster. As N decreases toward 200 or fewer atoms, some properties of the element change drastically. One example is the ionization potential, as compared to the bulk work function. Both represent the energy required to remove an electron from an atom, but the ionization potential is for a single, isolated atom whereas the bulk work function is for a mass of material. Interestingly, the ionization potential is usually around twice the work function. This is one example of how macroscopic, or bulk, behavior varies from quantum behavior.

In the realm of high surface area materials, unique quantum properties emerge in the form of novel electronic, magnetic, chemical and structural properties for small clusters. The diffusion of molecules through high surface area porous (molecular sieving) materials cannot be explained by traditional hard sphere molecule and fixed wall aperture models. Finally, catalysts with one, two or three dimensions on the nanometer scale have unique catalytic and chemical activity, as previously mentioned. (Siegel 52)

High surface area carbon materials are of particular interest. Included are fullerenes and nanotubes. Carbon nanotubes can be used as a template for the formation of an inorganic oxide nanotube. Porous carbons act as molecular sieves and may be useful for the storage of hydrogen or methane gas. (Siegel 61)

## Carbon Nanotubes and Nanodevices

At some point, the miniaturization of silicon-based electronic devices will become physically infeasible or financially impractical (Siegel 67). Research into the use of carbon nanotubes and the creation of single-charge electronics is therefore of interest.

Carbon nanotubes can be conducting, semiconducting or insulating depending on the diameter and "twist" angle and so they are of particular interest in the scaling down of electronics. A single walled nanotube (SWNT) consists of a graphite sheet, rolled into a tube, and capped on either end with a hemisphere of carbon. Multiwalled nanotubes (MWNT) are single walled nanotubes shelled within other nanotubes. If the graphite hexagons of a SWNT are symmetric along the axis of the tube, it is electrically conducting. If the hexagons are skewed slightly, the tube becomes semiconducting. Skewed further, the tube becomes an insulator. (Hughes 154) The use of carbon nanotubes in electrical components would overcome the problem of ill formed conductors in silicon chips. Other advantages include a higher packing density and better heat dissipation than traditional electronic materials. Additionally, current flowing through a nanotube is essentially ballistic, or one dimensional and without diversion. (Hughes 154)

Carbon nanotubes could have many other applications. Due to their unique molecular structure, nanotubes have been calculated to be 100 times stronger than steel and six times lighter ("Seeing is believing" 30). Methods of dispersing nanotubes uniformly through materials such as concrete as a strengthening agent are already being explored.

## CHAPTER IV: THE FUTURE

According to Mihail Roco, NSF Senior Advisor for Nanotechnology, "early payoffs [in nanotechnology]… will come in computing and pharmaceuticals, where powerful new tools and methods will benefit industries that already work at, or near, the molecular level." (Leo)

One way to assess the technologies that will be emerging onto the commercial market in the near future is to examine the patents that are being filed. According to Compano and Hullman, "slightly more than one-quarter of all patents filed are focused on the instrumentation" (Compano 245). This indicates that nanotechnology is still in its infancy, when the tools are being developed that will enable the development of new technologies. Industrial sectors that are filing commercially applicable patents include information technologies (IT) and pharmaceuticals. "Massive storage devices, flat panel displays or electronic paper are prominent IT patenting areas" (Compano 245). In the sector of pharmaceuticals, patents for "drug delivery, medical diagnostics, cancer treatments etc" (Compano 245) are prominent.

### Recent Advances in Supramolecular Chemistry and Nanotechnology

Researchers at Rice University have discovered a method of dispersing single-walled carbon nanotubes at industrially useful concentration. Using a process similar to the one used in the production of Kevlar, this technology may someday soon be used to create "ultralight, ultrastrong, materials with remarkable electronic, thermal, and mechanical properties" (Halford).

An open-cage fullerene has been synthesized by a group in Japan. The opening is large enough to allow the efficient entry of a hydrogen molecule. Innovations like this could have applications in hydrogen fuel storage. (Borman 47)

A group at IBM has generated an electrical current within a carbon nanotube by irradiating the nanotube with light. Functionalizing nanotubes with dichlorocarbene has been shown by a group at the University of California, Riverside, to change the conductive metallic nanotubes into semiconductors. Methods for the separation and manipulation of metallic and semiconducting SWNTs have been found. (Borman 47) As reported in *Nature*, the combination of palladium connecting wires and wide diameter nanotubes reduces the energy barrier (the "Schottky barrier") faced by electrons crossing from the metal wire into nanotubes. (Tersoff) These innovations open many possibilities for the practical application of nanotubes in electronic devices.

A collaboration between the University of California, Berkeley, and Lawrence Berkeley National Laboratory produced the first "nanometer-sized, electrically driven synthetic motor" (Borman 48). The motor is composed of a gold rotor and MWNT on a silicon chip. The motor could one day be used to power a nano-scale machine.

Numerous advances have been made in display related molecular electronics. These advances could "simplify the fabrication and increase the brightness of displays, light sources, and color switches" (Bormann 48). Other innovations have opened the door for "flat-screen, full-color organic light-emitting diode displays" (Bormann 48) and the manufacture of liquid-crystal displays in non-clean-room conditions.

**Nanomedicine**

The prospects in health care are very promising. One of the most significant problems in medicine is getting the medicine to the proper site in the body. Drugs taken orally undergo what is termed the "first pass effect" as they pass through the liver where significant metabolism occurs. The use of nanocapsules can help drugs survive the liver. Nanosizing of drug particles can help the drug to permeate tumor pores. (Arnall 31) "Pharmacy-on-a-chip" technology could be used as an artificial means of monitoring and regulating hormone levels in the body. This could be used in the treatment of type I diabetes, where the hormone insulin is under expressed causing unregulated blood sugar levels. Nanostuctured materials could be used in the production of stronger, lighter prosthetics. Biocompatibility of such prosthetics could also be improved. (Arnall 31)

**The Role of Investors and Vested Interests**

Unfortunately, investors could have a very large impact on the future of nanotechnology. Much like the "burst technology bubble of 2000" (Mulhall 53), if investors become disillusioned by "'nanostocks' that provide nano returns," (Mulhall 244) the advancement of the technology would be stymied. This could occur as a result of real nanotechnology companies having limited financial returns or due to overuse of "nano" as the new buzz word. Another hurdle that nanotechnology may face in the future may be vested interests resisting the adoption of new technologies. (Mulhall 53)

**Nanotechnology's Public Image**

A consumer backlash against emerging nanotechnologies may occur. This possibility has been acknowledged by a number of individuals, who have likened it to the backlash against genetically modified crops. The backlash against nanotechnology may even be worse, as a result of the loss of credibility that the scientific community has faced due to the GM foods fiasco. (Mulhall 268-269) Emmanuelle Boubour, a leading authority on nanoethics, says, “Scientists think about things like ethics, but they don’t let it interfere with their work” (Herrara). But with environmental groups like Greenpeace preparing to make nanotechnology their next big campaign, it may be necessary for scientists to respond to their concerns and allegations, however unfounded. Mark Modzelewki, the director of the Nanobusiness Alliance, predicts,

> Corporations will actually be puzzled that they are working towards good environmental stewardship, and these [anti-nanotechnology] groups are referencing extreme and absurd science fiction issues. (Lerner)

The idea of out-of-control nanobots, as depicted in Michael Crichton’s science fictional *Prey*, is by far the most sensational concern about nanotechnology and seems to be the driving force behind most anti-nanotechnology sentiment. Unfortunately, concerns about this so-called “grey goo” scenario, “diverts attention from areas where there may be real ethical and environmental concern” (“Goo and evil”). In order to avoid a media nightmare, advocates for nanotechnology will have to emerge, educating the public on the true concerns while eliminating wide-spread misconceptions.

## CHAPTER V: OPINIONS

Nanotechnology might cure disease, eliminate poverty, labor, and pollution; dramatic improvements in health care through nanotechnology could increase lifespan and quality of life. Advancing computer technologies combined with pervasive use of solar power could interconnect every human with every electric appliance on the planet.

Visions of the future range from the utopian to the dystopian, with seemingly very few differences between the descriptions except for perspective. For example, the above description may sound utopian, but consider the implications: increased lifespan would increase the world population, probably to unsustainable levels; pervasive use of computers would potentially open the entire planet to attack by a hacker. Molecular assemblers could just as easily eliminate labor as cause a massive worldwide arms race.

Virtually any seemingly fantastical idea presented in any science fiction novel may become reality with the maturation of nanotechnology. But, as Harold Craighead, the head of Cornell University's Nanobiotechnology Center, warns, "If people get the expectation that [science-fiction-like] things are achievable in the near term, they'll end up disappointed" (Aeppel).

**Molecular Assemblers**

The invention of a molecular assembler would be very interesting, although it is open to debate whether it is even feasible. It seems that most of the scientific community agrees with Professor Smalley of Rice University, who asserts that Drexler's "assembler cannot be built, and will not operate, using the principles [he] suggest[s]" (Drexler and Smalley, C&EN). There is at least a small camp of individuals, however, who believe in Drexler's vision. The goal of the Zyvex corporation, for example, is:

> To develop practical uses for molecular nanotechnology to transofrm [sic] how we make physical goods — creating clean, flexible, and powerful manufacturing for the 21st century. ("About Us…")

'Molecular nanotechnology' is the term coined by Drexler to describe "a technology based on the ability to build structures to complex, atomic specifications by means of mechanosynthesis" (*Nanosystems* 527). Essentially, Zyvex was formed with the goal to create the first universal assembler. The Foresight Institute, founded by Drexler and Christine Peterson, is "a nonprofit educational organization formed to help prepare society for anticipated advanced technologies." They also state that their "primary focus is on molecular nanotechnology" ("About the Foresight Institute"). With so many believing in the possibility if not inevitability of molecular nanotechnology, it deserves consideration.

And consideration it has received. All over the internet, one can find arguments in support of molecular nanotechnology and refutations of arguments against it (see for example "The Atkinson-Phoenix Nanotech Debate" or "Is the Revolution Real?"). It would appear that the believers are much more outspoken than the skeptics. It would also appear that the believers claim victory in debates when it is not necessarily warranted. The Foresight Institute, for example, claims a victory for Drexler in the debate with Smalley published in *Chemical & Engineering News*. I found that debate to more or less end in a draw: neither side seemed to sufficiently prove their case to the other.

Ultimately, it seems that the physics and chemistry of molecular nanotechnology have yet to really be worked out. The believers frequently cite Drexler's *Nanosystems* or *Engines of Creation*, seemingly as fact rather than theory, which, to me, hurts rather than helps their arguments.

**Life Extension**

Beginning with Drexler's analysis in *Engines of Creation*, life extension has been intimately intertwined with molecular nanotechnology. Indeed, with the advancement of nanomedicine, quality of life will be improved, and people will, likely, live longer, healthier lives. I propose the following question: how far do we want to go?

In another example of how the proponents of molecular nanotechnology seem only to hurt their own case, take this analysis of the ethics of gene modification as a means of life extension:

> It is likely that some conditions will be treated most easily by modifying the body's genetic material. Many people are disturbed by this idea, especially if the modification is transmissible to offspring. However, once we have a nanotechnology that can directly manipulate the genes, transmission of modified genes need not be a cause for concern. Any genetic manipulation that turns out to be a bad idea will be reversible. Furthermore, it would be trivial to edit the DNA of any offspring while still in embryo stage in order to remove the modifications. The idea that a genetic modification will irreversibly change the whole species becomes incorrect once genes can easily be directly manipulated. (Phoenix, "…Life Extension")

Perhaps it should be seriously considered that any genetic modification of our species is unethical. This possibility is not even considered! In fact, the proposed solution for those that are weary of genetic modification is… more genetic modification!

## CHAPTER VI: PROPOSED BENEFITS

Nanotechnology, not unlike any other technology, will yield benefits. Nanotechnology, quite uniquely, will yield benefits across many, many fields and disciplines. This is mainly due to the breadth of the field itself but also because any given nanoscience could have a vast breadth of potential applications. Lighter, stronger materials, for example, could be used in the construction of buildings, cars, clothing, and so on until infinity.

Improved fuel efficiency and novel fuel storage systems from nanotechnology could make methane or hydrogen fuel cells commercially feasible. (Arnall 32) The implications of decreased fossil fuel use and increased reliance on more environmentally fuels are dramatic.

Improvements in health care will be immense as well. New diagnostic technologies will become available; drug delivery will be optimized. (Arnall 31) The result will be more people living longer lives with greater quality of life as well.

Computers will become smaller, lighter, and more energy efficient. Carbon nanotubes incorporated into electronics will yield novel memory and storage systems, display technologies, and E-paper. (Arnall 29) Virtual reality could become a reality, freeing us from the restrictions of the workplace (Mulhall 88).

**Solar Energy**

The promise of cheap solar cells is immense. Nanotechnology could make the incorporation of solar cells into virtual every surface possible. “Solar cells might be painted invisibly on cars, buildings, and sidewalks” (Mulhall 115). Perhaps ironically, the invention of cheap solar cells might cause a massive increase in energy consumption, maintaining a certain level of dependence on fossil fuels and other energy sources. (Mulhall 60) This diversity would be an advantage, protecting us from catastrophic loss of electricity. (Mulhall 215) Importantly, the emergence of solar power seems to have very few negative consequences.

**Nano-Computers**

The impact of computer miniaturization and decreased cost of production will certainly cause pervasive incorporation of computers into any and all products. Whether that is good or bad is open to discussion, but there is undeniable potential for nanoelectronics in the future.

## CHAPTER VII: RISKS

As with any technology, there are risks associated with nanotechnology. Nanoparticles have been shown to have health effects and may have environmental risks as well. There are some other risks to be associated with nanotechnology, and molecular nanotechnology as proposed by Drexler in particular, including possible effects from the increased use of computers and more impressively, threats to the entirety of human existence.

### The Environment

Pollution is a serious concern about nanotechnology. Even current nanotechnologies are potentially very harmful to the environment. Nanoparticles are dangerous to the environment for the same reason that they are useful: because the properties of nanoparticles differ from bulk materials and are often very unique. Nanoparticles could, for example, "be inhaled, causing harm to humans, or could bind with poisonous metals and help disperse them through the environment" (Regalado). To this extent, the concern of environmental groups is warranted.

A product called SoilSET has been used on a large scale to prevent erosion without approval from the EPA. The product is not composed of nanoparticles, but the mixture of components reacts with water yielding a nano-scale binder which effectively forms a crust over a surface of soil, protecting it from erosion. The EPA did not require approval of this product because it contains chemicals that have been used for environmental applications before. The Action Group on Erosion, Technology, and Concentration (ETC) cites this product, however, as an example of irresponsible policy on the part of the EPA, since SoilSET is based on the formation of nano-scale structures which could have new environmental implications. (Felton 20) The ETC is a small environmental rights group based out of Winnipeg, Canada. Led by Patrick Mooney, the ETC has previously lead "high-profile campaigns against bioprospecting and genetically modified foods" (Brumfiel 246). In March 2002, the ETC called for a worldwide moratorium on nanotechnology research, because of environmental concerns. Judging from the impact that the ETC had in the recent genetically modified foods debate, their concerns about nanotechnology should not be taken lightly.

**Human Health**

There have been many concerns voiced about the effects of nanoparticles on human health. In most cases, the effects of nanoparticles are little different from the effects of asbestos or dust inhalation, but any number of studies are currently receiving funding to determine the extent of the danger.

Researchers at Dupont found that mice exposed to carbon nanotubes either died immediately or recovered rapidly showing no long term effects. Their conclusion was that the nanotubes aggregated and caused some of the mice to suffocate. Those mice that did not suffocate indicated that recovery from nanotube exposure is facile. (Felton 19) It has been shown by the West Virginia University in collaboration with the National Institute for Occupational Safety and Health that the metal catalysts used to create nanotubes, which remain part of the tubes unless they are specifically treated to remove them, can cause oxidative stress to skin cells. (Felton 20) The effect of materials with novel properties on the human body will likely be equally novel; caution is therefore justified.

## Personal Privacy

As nanotechnology develops and we come to rely more heavily on electronics, issues such as identity theft will become even more serious. As one author put it, "Personal privacy is dead and getting deader" (Mulhall 80). Some of the implications of increased reliance on computers are daunting, but they need not necessarily be attributed to nanotechnology.

## Human Existence

Nick Bostrom, of the Faculty of Philosophy at Oxford University, ranks "deliberate misuse of nanotechnology" as the most probable global, terminal (i.e. existential) risk to humanity, followed by nuclear holocaust. "Accidental misuse of nanotechnology" ranks sixth on his list, just behind a "genetically engineered biological agent." (Bostrom) The combined risk of accidental and deliberate nanotechnological disasters is quite distressing. As nanotechnology develops, especially if it develops to the extent of Drexler's envisioned level of molecular nanotechnology where assemblers are commonly available, the risk of deliberate nanotech-terrorist attacks, a worldwide nanotechnology arms race, or the accidental release of self-replicating nanobots will have to be carefully considered.

In *Engines of Creation*, Drexler considers these same dangers and agrees, "We cannot afford certain kinds of accidents with replicating assemblers" (216). He elaborates:

> Replicators can be more potent than nuclear weapons: to devastate Earth with bombs would require masses of exotic hardware and rare isotopes, but to destroy all life with replicators would require only a single speck made of ordinary elements. Replicators give nuclear war some company as a potential cause of extinction, giving a broader context to extinction as a moral concern. (218)

Drexler's conclusion is that we must prepare for the inevitability of molecular nanotechnology and replicators. The dangers that he depicts are quite scary; whether or not the risks are real is debatable.

## CHAPTER VIII: SURVEY RESULTS

Several professors belonging to the WPI community were interviewed. In addition, e-mail surveys were sent to a number of individuals in academia and industry. The individuals who responded at length and with the most enthusiasm were those involved with websites dedicated to the discussion and coverage of nanotechnology. The respondents clearly fall into two categories: those that believe molecular nanotechnology will be realized and those that do not.

The individuals that strongly believe that molecular nanotechnology (MNT) can and will be realized are those who already publicly link themselves to the Foresight Institute and K. Eric Drexler. They are also involved in the administration of organizations and websites such as the Center for Responsible Nanotechnology (http://CRNano.org) or Nanotechnology Now (http://nanotech-now.com). They assert that the position of those who dismiss MNT as impossible is deteriorating. As a whole, opinions for the future are optimistic, but there are some concerns about the development of policy. For example, Chris Phoenix, of the Center for Responsible Nanotechnology, expressed concern that the National Nanotechnology Initiative is focusing on "traditional" (in other words, non-MNT) nanotechnology, when the development of MNT would have a much more drastic societal impact. Rocky Rawstern, of Nanotechnology

Now, expressed concern over the lack of a MNT feasibility study in the 21st Century Nanotechnology Research and Development Act.

In his e-mail response, Chris Phoenix predicts benefits such as "greater health and longer life, cheaper and cleaner manufacturing, easier access to space, better environmental awareness, universal access to computers, smarter products, and acceleration of research in many fields." Similarly, Rocky Rawstern predicts advances in "fuels cells, catalysts, solar cells, computer chips and memory," textiles, medicine, and materials science. The benefits and concerns expressed by Drexler in *Engines of Creation* are reiterated. The "gray goo" scenario is debunked as possible, but extremely unlikely. Chris Phoenix adds that a grey goo scenario could only be brought about deliberately and by someone with malicious intentions, comparable to the invention and distribution of a computer virus.

Even though in his e-mail response Rocky Rawstern, of Nanotechnology Now, states that "to date, *nobody* has presented a *scientific* argument that casts doubts on MNT," the majority of respondents from academia seem unconvinced of the possibility of MNT. Of the professors surveyed at WPI, some were not familiar with the Foresight Institute or K. Eric Drexler. Those that were familiar indicated that their "gut feeling" about MNT was that it was not viable. Professor Henry I. Smith at the Massachusetts Institute of Technology seemed offended at the mere mention of MNT. When asked about the possibility of nanotechnology posing a threat to the future, Professor Smith responded:

> Science fiction has always promoted threat scenarios. None should be taken seriously... Science is found in scientific journals, not self promoting literature from institutions such as the Foresight Institute...

> Believe what you read in journals published by scientific societies. Treat the rest with due caution.

It may not have been entirely clear to Professor Henry that the purpose of this investigation has been to consider all opinions and points of view, but his response is valid. Similarly, Professor Nadrian C. Seeman at New York University responded, "Nonsense. Nanotechnology is just chemistry." Even though the Foresight Institute seems to have a following, with learned individuals such as Professor Seeman and Professor Smith dismissing them as writers of science fiction, it is hard to believe their "self promoting literature." Professor Nancy Burnham at Worcester Polytechnic Institute acknowledged Drexler's *Engines of Creation* because it "made you think." Perhaps that justifies the Foresight Institute as a legitimate organization: even if they ultimately prove to be misguided, by stimulating dialogue and inspiring awareness they have served a very useful purpose.

Both MNT believers and non-believers alike agree that policy is essentially headed in the right direction, funding is being supplied to proper areas and that the future of nanotechnology is bright. Rocky Rawstern, of Nanotechnology Now, for example, feels that the genetically modified organisms "debacle will help guide policy on timely and accurate dissemination of nanotechnology information," allowing the avoidance of a public backlash. Professor Nancy Burnham at the Worcester Polytechnic Institute mentioned that Michael Crichton's *Prey* is going to be made into a movie and there are already plans to film a documentary to be included on the DVD release which will explain the actual research conducted at the laboratory used as the main setting. This concern for the public opinion is reassuring; anything that helps separate fact from fiction is always in the best interest of both science and society.

## CHAPTER IX: CONCLUSIONS

As a species, humans are going to have to get their act together. As Bill Joy pointed out in "Why the Future Doesn't Need Us," maybe the pursuit of science and knowledge is not necessarily an integral part of the pursuit of a utopian society. According to Bill Joy, the Dalai Lama, in *Ethics for the New Millennium*, argues that we must "acknowledge the strong evidence that neither material progress nor the pursuit of the power of knowledge is the key [to happiness] – that there are limits to what science and scientific pursuit alone can do" (Joy). We must consider the possibility that the pursuit of nanotechnology, or at least molecular nanotechnology, may be too dangerous for humanity. Alternatively, we may not find meaningful existence in the future if molecular nanotechnology couples with artificial intelligence and rampant genetic engineering. As Bill McKibben, the author known for his best-selling book *The End of Nature*, recognized, "The proponents of this kind of work anticipate the disappearance of humans with ill-disguised glee. They speak of a 'post-human future,' or 'fast-forwarding our evolution.'" Honestly, these possibilities simply do not appeal to me. How can 'post-human' possibly be interpreted as anything but depressing?

Having said all that, it is only appropriate to consider nanotechnology as a natural and simple extension of current technologies. Is there any reason to believe that molecular nanotechnology will develop, revolutionizing… well, everything? The answer seems to be "no." Without entering into the science too deeply, it does not seem feasible to be able to economically build macroscopic structures through molecular manufacturing. Although the mechanical deposition of atoms has been demonstrated and modeled, the expense of the tools and manpower required for even the simplest act are immense. The idea of a swarm of nanobots manufacturing items atom by atom is both intriguing and terrifying, but current science simply does not support or even suggest the eventual realization of such a technology. The true science of self assembly is simply an extension of chemistry, the natural progression of which may one day allow the inexpensive manufacture of solar cells, for example. The ability to create structures with features on the nanometer scale may allow the development of faster, more efficient computers, stain resistant fabrics, self-washing windows, and clear sunscreen, but the development of seemingly sentient inorganics hell-bent on world domination is more than a bit of a stretch, although it certainly makes good science fiction.

Some concerns about the future seem valid. For example, as our ability to manipulate genetic material and our understanding of biology increase, we can expect to see medicine advance in leaps and bounds, but the same science would also enable the development of viruses and chemical weapons more potent than any previously seen. Even if we trust humanity to effectively stop or counter such deliberate evils, the possibility of accidents is still important to consider. Industrial accidents do occur; chemicals are, on occasion, accidentally released into the environment. Since nanoparticles exhibit unique properties which imbue them with their very usefulness, their effect on the environment must be considered. These risks, however, are not fundamentally different from the risks of the accidental release of any chemical.

I cannot possibly over emphasize the importance of education. Even if nanotechnology is a mere extension of chemistry, some may still be afraid. Chemistry is not something that should be feared, nor should the term "chemical." Water, after all, is a chemical, and chemical reactions are occurring continuously in the environment and our bodies. Chemicals only become lethal and dangerous when they are involved in accidents or are deliberately exploited for their toxic properties. Safety precautions and federal regulation are put in place in order to minimize those risks. In the end, that is all we can do: be aware of the risks and prepare ourselves for them. And as far as nanotechnology is concerned, I believe we are headed in the right direction, but then again, only time will tell.

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## APPENDIX: INTERVIEW SUMMARIES & E-MAIL TRANSACTIONS

**Burnham, Nancy A., Associate Professor of Physics, WPI. Personal Interview. 23 April 2004. Summary:**

Consent was given to record the interview. Nanotechnology is a very broad term, with two main ways of defining it. First, there is the mechanistic definition: anything with a dimension less than one micron or anything smaller than the wavelength of light. The second definition involves the novel properties and unique behaviors of small systems where quantum effects become prominent: the "small is different" mantra. These definitions differ from simple miniaturization as in computer components such as the Pentium® 4 which has a nanometer-scale gate width. A recent article in *Nature* discussed the newly developed capability to manufacture carbon nanotubes of any length, which could have a very large impact. New devices and the self assembly of molecules were also discussed as interesting. "Nano" being the new buzz word and the National Nanotechnology Initiative were mentioned. Michael Crichton's *Prey* is being made into a movie and a bonus feature for the DVD is being filmed which describes the actual research conducted at the filming location. The government is aware of the possibility of a public scare and research into the effects of nanoparticles, such as fullerenes, in animals, such as fish, is receiving funding. The Foresight Institute and Drexler were discussed. *Engines of Creation* contained some scary ideas, but importantly, it made the reader think. Nanotechnology's impact on the future cannot be accurately anticipated; it should be compared to the development and impact of computers. It is reassuring that we are acting sensibly with nanotechnology, being aware of the future, looking into the effects that a release of particles could have.

**Papageorgiou, Demetrios P., Assistant Professor of Electrical & Computer Engineering, WPI. Personal Interview. 3 Mar. 2004. Summary:**

Consent was given to record the interview. Nanotechnology was defined in terms of shrinking transistors and other electromechanical structures of very small scale. Because nanotechnology is such a wide field, defining the field may possibly be the hardest part. Intel® was recognized as an industrial leader in the development semiconductors with nano-scale features. Novel materials and biomedical applications were also discussed. In the future, further and greater interfacing with biological systems will ultimately yield an improvement in quality of life. In the distant future, the possibility of nanobots in the blood could diagnose and treat nearly any disease. One other possible application that is currently being investigated for military purposes is the invention of clothing that heats and cools the wearer, regulating their body temperature. The same technology could be used in the treatment and prevention of hypothermia. New technologies will reduce emissions. Abuse of nanotechnology was one concern about the future. Advancing technologies will make it possible for an individual to create their own virus.

**Thalladi, Venkat R. Assitant Professor of Chemistry, WPI. Personal Interview. 23 April 2004. Summary:**

Consent was given to record the interview. Defining nanotechnology is difficult. It should be defined not in terms of size, but instead in terms of the new capabilities and possibilities opened by operating at that small size. The bottom-up approach to manufacturing was discussed: using molecules to build structures which are incorporated into functional devices. Miniaturization is seeing the limitations of the top-down manufacturing approach. Drexler's ideas, with regard to the article in *C&E News*, seem implausible, but admittedly, that opinion is merely a gut feeling which may have been influenced by his past experience and the opinions of those involved. Microscopic is cheaper and less expensive. Like quantum mechanics, nanotechnology will bring developments in the future which cannot possibly be predicted. However, it does not seem that something bad is coming our way. Quantum dots are made of toxic elements, cadmium and selenium, for example, and we do not really know how they might affect the human body, especially since there are potential applications as carriers within the human body, mimicking biomolecules in size.

**Thompson, Robert W., Professor of Chemical Engineering, WPI. Personal Interview. 28 April 2004. Summary:**

Consent was given on record to record the interview. Zeolites and their nanometer precursors were discussed prominently. Zeolites are porous materials with pores as small as tenths of a nanometer. There are catalytic applications, as well as filtration applications for both water and air. A method of remediation of water with the use of zeolites has been demonstrated for the removal of organic chemicals. Another possible application is the removal of ethanol from alcoholic drinks such as wine or beer for those who do not wish to imbue alcohol but would like to drink wine or beer. Zeolites are an example of templated assembly. As far as the future is concerned, there is some concern for the inhalation of airborne particulates. Zeolites have been compared to asbestos as lung irritants.

From: Nadrian C Seeman [ncs1@scires.acf.nyu.edu]
Sent: Friday, April 23, 2004 5:06 AM
To: Chad Kormos
Subject: Re: Undergraduate Nanotechnology Survey

Hi Chad:

On Thu, 22 Apr 2004, Chad Kormos wrote:

I am an undergraduate at Worcester Polytechnic Institute in Worcester, Massachusetts. As part of our requirement for graduation, each student must complete an Interactive Qualifying Project (IQP). The goal of the IQP is to produce competent professionals who understand the societal implications of science and technology. For my IQP, I have chosen to investigate the growing field of nanotechnology.

As part of my research, I am surveying some selected individuals intimately familiar with the field of nanotechnology in order to develop my understanding.

If you could spare a few minutes, I would like your opinion on a number of questions concerning nanotechnology. You can reply to this email with your brief responses to the questions below, or if a phone interview would be more convenient or easier for you, I'd be very pleased to speak with you; just provide me with a phone number and a time that would be convenient.

Since nanotechnology is such a broad field, how do you define it in terms of your own interests?

> I do DNA nanotechnology, making objects, devices and arrays from branched DNA molecules.

What recent developments in nanotechnology interest you the most? What would you like and expect to see in the near future?

> The recent construction of a Sierpinski triangle from DNA tiles and the recent development of a clonable DNA octahedron.

What impact will nanotechnology have on society in the future? What sorts of benefits do you expect to come from advancing nanotechnologies?

> I expect that we will have faster computers, more readily available drug leads, the ability to make new substances, and new materials.

Do you have any concerns about the future and nanotechnology? For example, do you foresee nanotechnology facing serious opposition from the public or environmental rights groups (much as genetically modified foods have)? Do you believe nanotechnology will develop to the point where it is a threat to human existence, as some of my sources have suggested?

Nonsense. Nanotechnology is just chemistry.

In order for me to incorporate your opinions into my final paper, I'll need your response by Friday, April 30. Thank you for your participation!

Chad Kormos
WPI

Sure.

Best,

Ned Seeman

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From: Henry I. Smith [hismith@nano.mit.edu]
Sent: Sunday, April 25, 2004 3:03 PM
To: Chad Kormos
Cc: Henry Smith
Subject: Re: Undergraduate Nanotechnology Survey

On Thursday, April 22, 2004, at 11:48 PM, Chad Kormos wrote:

I am an undergraduate at Worcester Polytechnic Institute inWorcester, Massachusetts. As part of our requirement for graduation, each student must complete an Interactive Qualifying Project (IQP). The goal of the IQP is to produce competent professionals who understand the societal implications of science and technology. For my IQP, I have chosen to investigate the growing field of nanotechnology.

As part of my research, I am surveying some selected individuals intimately familiar with the field of nanotechnology in order to develop my understanding.

If you could spare a few minutes, I would like your opinion on a number of questions concerning nanotechnology. You can reply to this email with your brief responses to the questions below, or if a phone interview would be more convenient or easier for you, I'd be very pleased to speak with you; just provide me with a phone number and a time that would be convenient.

Since nanotechnology is such a broad field, how do you define it in terms of your own interests?

> I define it as requiring features with dimensions below 100 nm in at least two dimensions.

What recent developments in nanotechnology interest you the most?

> Our ability to do templated self assembly

What would you like and expect to see in the near future?

> A focus on funding for the development of lower cost tools for nanostructure fabrication. We need better tools but there is a funding problem.

What impact will nanotechnology have on society in the future? What sorts of benefits do you expect to come from advancing nanotechnologies?

> Nanotechnology is not new, just the extension of the development of science and engineering. Science and engineering have always impacted society. I do not subscribe to any of the hysteria promoted by the Foresight Institute about the dangers of nanotechnology. This is science fiction.

Do you have any concerns about the future and nanotechnology? For example, do you foresee nanotechnology facing serious opposition from the public or environmental rights groups (much as genetically modified foods have)?

No

Do you believe nanotechnology will develop to the point where it is a threat to human existence, as some of my sources have suggested?

Science fiction has always promoted threat scenarios. None should be taken seriously. You appear to be listening to non scientific sources. Science is found in scientific journals, not self promoting literature from institutions such as the Foresight Institute. Recall the movie 2001 where the computer takes over? Don't worry about such science fiction stories. Be careful what you use as sources. Good research requires confidence in one's sources. Scientific societies were created to screen out the nonsence from the real. Believe what you read in journals published by scientific societies. Treat the rest with due caution.

H. I. Smith

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From: Rocky Rawstern [rocky@future-is-here.com]
Sent: Friday, April 23, 2004 2:05 PM
To: Chad Kormos
Cc: Brian@Nanotech-Now.com
Subject: Re: Undergraduate Nanotechnology Survey

Dear Chad,

Good questions, for which you will find my answers imbedded below:

Since nanotechnology is such a broad field, how do you define it in terms of your own interests?

The term "nanotechnology" has evolved over the years via terminology drift to mean "anything smaller than microtechnology," such as nano powders, and other things that are nanoscale in size, but not referring to *mechanisms* that have been purposefully built from nanoscale components. See our "Current Uses" page for examples. This evolved version of the term is more properly labeled "nanoscale bulk technology," while the original meaning is now more properly labeled "molecular nanotechnology" (MNT), or "nanoscale engineering," or "molecular mechanics," or "molecular machine systems," or "molecular manufacturing." Recently, the Foresight Institute has suggested an alternate term to represent the original meaning of nanotechnology: zettatechnology.

At the most basic *technical* level, MNT is building, with intent and design, and molecule by molecule, these two things: 1) incredibly advanced and extremely capable **nano-scale** and micro-scale machines and computers, and 2) ordinary size objects, using other incredibly small machines called **assemblers** or fabricators (found inside nanofactories). In a nutshell, by taking advantage of quantum-level properties, MNT allows for unprecedented control of the material world, at the nanoscale, providing the means by which systems and materials can be built with exacting specifications and characteristics. Or, as Dr. K. Eric Drexler puts it "large-scale mechanosynthesis based on positional control of chemically reactive molecules."

What recent developments in nanotechnology interest you the most? What would you like and expect to see in the near future?

Two things interest and concern me the most:

1) In December of 2002, the Center for Responsible Nanotechnology was formed, giving voice to the concerns that many of us have regarding the safe development of molecular manufacturing (or molecular nanotechnology [MNT]. AKA: nanotechnology, the way it was once defined). CRN's stated mission, and one we support, is "CRN acts to raise awareness of the issues. We believe that even a technology as powerful as molecular manufacturing can be used wisely and well--

but that without adequate information, unwise use will be far too common. The mission of CRN is to raise awareness of the issues presented by nanotechnology: the benefits and dangers, and the possibilities for responsible use." You can learn more about them here http://crnano.org/

2) The omission of a feasibility study of molecular manufacturing from the 21st Century Nanotechnology Research and Development Act. The Act is a great step forward towards insuring that nanotechnology research is funded, but fails to address a fundamental question "is molecular manufacturing a viable technology?" To date, all the learned research suggests that it is. To date, *nobody* has presented a *scientific* argument that casts doubts on MNT. It was big business, in the guise of the Nanobusiness Alliance (1), that was responsible for changing the study to one on "molecular self-assembly," which we already know to be feasible. Glenn Reynolds says it best "*Given that self-assembling nanodevices have already been demonstrated, taking a narrow view of this language seems unlikely to accomplish much: It's like performing a study to determine the feasibility of integrated circuit chips. Been there, done that.*" To read more, check out our summary http://www.nanotech-now.com/MNT-12092003.htm

Also interesting is the rapid progression in our understanding of the properties of the nanoscale. As you know, at the nanoscale, classical physics gives way to quantum effects, producing some decidedly unusual and interesting possibilities. Ray Kurzweil talks about technological change being on a "double exponential" curve - he says this "So we won't experience 100 years of progress in the 21st century -- it will be more like 20,000 years of progress (at today's rate)." Given the rate at which we are learning to harness new discoveries, we can safely predict that we're in for a decidedly fast-paced ride. Let's hope we adequately prepare for it.

What impact will nanotechnology have on society in the future? What sorts of benefits do you expect to come from advancing nanotechnologies?

In the near future (today to five years out) we will likely see advances in materials science that yield stronger and/or lighter materials. As has been the case in the past, the military is likely to be the major beneficiary of these advances, followed by the public. Already, a few products exist that take advantage of the "stronger/lighter" properties of nanoscale materials, such as the plastic nanocomposite being used for "step assists" in the GM Safari and Astro Vans, and in a bumper being produced by Toyota.

We are also likely to see advances in fuel cells, catalysts, solar cells, computer chips and memory (faster, smaller, producing less heat, larger memory capacity, less cost ...), sensors for homeland security, textiles (consider the "spill proof" shirts and pants already on the market), scaled down gene and protein array-based diagnostics, and many other areas.

Further out, say 5 to 10 years, we are likely to see a variety of medical advances, such as the cancer-detecting and fighting gold nanoparticle nanoshells being developed by Naomi Halas and Jennifer West at Rice University, and the in situ whole-blood immunoassay (based on gold nanoshells), also being studied and developed at Rice by Halas and West. To learn more, see our Best Discoveries page, here http://nanotech-now.com/2003-Awards/Best-Discoveries-2003.htm, and see also the Best Discoveries Runners Up for 2003, here http://nanotech-now.com/2003-Awards/Best-Discoveries-Others-2003.htm - over 60 other promising nanotech-enabled discoveries, from drug delivery to cancer diagnosis and treatment.

Past 10 years out it is very difficult to predict how and which technologies will change our lives. Some predictions for mature nanotechnology include (paraphrasing Dr. K. Eric Drexler):

Nearly free consumer products
PC's billions of times faster then today
Safe and affordable space travel
Virtual end to illness, aging, death
No more pollution and automatic cleanup of existing pollution
End of famine and starvation
Superior education for every child on Earth
Reintroduction of many extinct plants and animals
Terraforming Earth and the Solar System

What is a given is that as advances in our understanding of scientific principles increase, so too does our world change. Time and again, new technologies have radically changed the very fabric of our society. As they say "change happens," and never before at the pace we see today.

Do you have any concerns about the future and nanotechnology? For example, do you foresee nanotechnology facing serious opposition from the public or environmental rights groups (much as genetically modified foods have)? Do you believe nanotechnology will develop to the point where it is a threat to human existence, as some of my sources have suggested?

While I have a general concern for public perception, I feel that understanding the GMO debacle will help guide policy on timely and accurate dissemination of nanotechnology information. An interview with Clayton Teague (director of the National Nanotechnology Coordination Office) conducted by Howard Lovy of Small Times, gives me hope that our government has learned the lesson, and will make a greater effort to communicate with the public; whether or not this effort is successful depends on *how* open they are.

Will nanotechnology ever be a threat to human existence? Quite possibly, depending on how fast we develop MNT, and how quickly we spread the technology. While it may seem that the last sentence advocates slowing down, quite the opposite is true - we need to *greatly increase* our efforts to understand the nanoscale, and apply that knowledge to MNT. I won't try to list all possible dangers and benefits, as the folks at CRN have already done an outstanding job in those (and other) areas. See **Dangers of Molecular Manufacturing** http://crnano.org/dangers.htm and **Benefits of Molecular Manufacturing** http://crnano.org/benefits.htm.

In the not-so-distant future, don't be surprised to wake up one morning to find that your world has changed beyond anything you could have imagined.

(1) http://www.smalltimes.com/document_display.cfm?document_id=7279

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In order for me to incorporate your opinions into my final paper, Ill need your response by Friday, April 30. Thank you for your participation!

Chad Kormos
WPI

From: Chris Phoenix [cphoenix@CRNano.org]
Sent: Tuesday, April 27, 2004 12:13 PM
To: Chad Kormos
Cc: mtreder@CRNano.org
Subject: Re: Undergraduate Nanotechnology Survey

Sorry for the delay answering. My email only delivered this last night.

I'll answer your questions; I don't know whether Mike has time right now.

Chad Kormos wrote:

Since nanotechnology is such a broad field, how do you define it in terms of your own interests?

There's no one definition. We're more concerned with accurate communication with whoever we're talking to. Our interests are mainly on the most advanced and powerful kind of nanotechnology, which we often call "molecular manufacturing" to distinguish it from the nanoscale technology that the National Nanotechnology Initiative focuses on.

What recent developments in nanotechnology interest you the most? What would you like and expect to see in the near future?

On the science side, several kinds of lithography have now reached 20 nanometers. And a 22-nanometer molecular shape of DNA was designed and built semi-automatically. Top-down and bottom-up can now work together, and we should see some very complex and functional devices produced.

On the policy side, the position of those who say molecular manufaturing can't work is looking weaker all the time. And a group in Russia has started actually working on it.

In the next few years, I expect massively impressive work on a wide variety of nanoscale and medical technologies. And a growing realization that molecular manufacturing is going to be an issue, probably within the next decade. Business may not care about it yet,
but policy people should be paying close attention. That's what I'd most like to see: policy people working on preparing for the development of a revolutionary manufacturing technology. It has a lot more implications than it sounds like.

What impact will nanotechnology have on society in the future? What sorts of benefits do you expect to come from advancing nanotechnologies?

The ability to make nanoscale machines even more cheaply and numerously than transistors can be made today? What won't it impact? It'll affect medicine and computation, of course. Weapons. Surveillance. And depending on the cost (though we think it'll be quite low), it could affect aerospace, consumer goods, and even construction.

The effects on most of today's issues will be good. Greater health and longer life, cheaper and cleaner manufacturing, easier access to space, better environmental awareness, universal access to computers, smarter products, and acceleration of research in many fields.

Do you have any concerns about the future and nanotechnology? For example, do you foresee nanotechnology facing serious opposition from the public or environmental rights groups (much as genetically modified foods have)? Do you believe nanotechnology will develop to the point where it is a threat to human existence, as some of my sources have suggested?

Molecular manufacturing, while mitigating some of today's problems, creates massive new issues. Really cheap manufacturing and rapid prototyping of cutting-edge equipment could be misused disastrously. Human rights issues: Anything you can automate for one person, whether tracking or monitoring or even interfering, you can apply to a whole population. And there'd be more than enough computer power to track everyone full-time, store full-time audio and video, synthesize a bird's eye view from any angle (even indoors), and automatically flag unusual events. What government wouldn't want that power? What government would you trust with it?

Then there's the possibility of an arms race. This would probably be unstable, since nano-built weapons will be easier to use than to stockpile (the opposite of nukes). And a nano-built war could be incredibly destructive. An un-augmented human would be absolutely helpless against a self-propelled robot weapon such as a nanofactory system could build by the millions. And I don't know whether offense or defense will be easier with this technology, but I suspect the advantage is with the offense.

Environmental problems: the manufacturing itself can be very clean, but what happens when people throw out the stuff they're done with? Also, this technology could be quite power-hungry. There's no such thing as too much computer power, and even though they'll be efficient by today's standards, it'll probably be quite cheap to build a megawatt worth of computers. So there'll still be scarcity of at least one sort: heat pollution credits.

A threat to human existence could come from any of several sources, some of them non-nanotech. But I think the first biggest threat would be massive war. We could easily make the earth uninhabitable with dispersed antipersonnel weapons.

While we're on the subject, I should mention gray goo. Gray goo is, as far as I know, theoretically possible--but difficult--it could only be done deliberately, not by accident. (Nanofactories are more efficient than assemblers, and not at all goo-like. Even assemblers couldn't turn into goo accidentally, but it's easier to realize why nanofactories are safe.) So eventually we'll have to worry about the scum who write computer viruses turning their attention to gray goo, and they could do serious--conceivably even humanity-threatening--damage if we're not prepared to prevent them and/or clean up the goo efficiently. But gray goo is inherently inefficient, since it has to haul around a computer, blueprint, chemical fabricator, and chemical preprocessor. It's just not very bad compared to some of the weapons that people will probably be building on purpose. So I'm a lot more worried about arms race than about goo at this point.

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If you need more information on any of these, please write back!

Chris

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