Nanotechnology: The Future is Coming Sooner Than You Think

A JOINT ECONOMIC COMMITTEE STUDY

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Abstract

Enhanced abilities to understand and manipulate matter at the molecular and atomic levels promise a wave of significant new technologies over the next five decades. Dramatic breakthroughs will occur in diverse areas such as medicine, communications, computing, energy, and robotics. These changes will generate large amounts of wealth and force wrenching changes in existing markets and institutions.

This paper discusses the range of sciences currently covered by nanotechnology. It begins with a description of what nanotechnology is and how it relates to previous scientific advances. It then describes the most likely future development of different technologies in a variety of fields. The paper also reviews the government's current nanotechnology policy and makes some suggestions for improvement.

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Nanotechnology:

The Future is Coming Sooner Than You Think

In 1970 Alvin Toffler, noted technologist and futurist, argued that the acceleration of technological and social change was likely to challenge the capacity of both individuals and institutions to understand and to adapt to it.[1] Although the world has changed a great deal since then, few would argue that the pace of change has had the discontinuous effects that Toffler predicted. However, rapid advances in a number of fields, collectively known as nanotechnology, make it possible that Mr. Toffler's future has merely been delayed. In fact, some futurists now talk about an unspecified date sometime around the middle of this century when, because of the accelerating pace of technology, life will be radically different than at any prior time.

This paper discusses the range of sciences currently covered by nanotechnology. It begins with a description of what nanotechnology is and how it relates to previous scientific advances. It then describes the most likely future development of different technologies in a variety of fields. The paper also reviews the federal government's current nanotechnology policy and makes some suggestions for improvement.

What Is Nanotechnology?

A nanometer (nm) is one billionth of a meter. For comparison purposes, the width of an average hair is 100,000 nanometers. Human blood cells are 2,000 to 5,000 nm long, a strand of DNA has a diameter of 2.5 nm, and a line of ten hydrogen atoms is one nm.[2] The last three statistics are especially enlightening. First, even within a blood cell there is a great deal of room at the nanoscale. Nanotechnology therefore holds out the promise of manipulating individual cell structure and function. Second, the ability to understand and manipulate matter at the level of one nanometer is closely related to the ability to understand and manipulate both matter and life at their most basic levels: the atom and the organic molecules that make up DNA.

Nanotechnology can be viewed on a variety of levels. The U.S. National Nanotechnology Initiative defines nanotechnology as:

> "[T]he science, engineering, and technology related to the understanding and control of matter at the length scale of approximately 1 to 100 nanometers. However, nanotechnology is not merely working with matter at the nanoscale, but also research and development of materials,

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[1] *Future Shock*, Amereon Ltd. (1970).

[2] *Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative*, National Research Council, Washington D.C., 2002, p. 5.

devices, and systems that have novel properties and functions due to their nanoscale dimensions or components"[3]

A joint report by the British Royal Society and the Royal Academy of Engineering similarly defined nanotechnology as "the design, characterization, production, and application of structures, devices and systems by controlling shape and size at nanometer scale."[4]

The application of nanotechnology can occur in one, two or three dimensions. Thus it includes the use of an oxygen plasma 25 atoms thick to bind a layer of indium phosphide to silicon in order to make a computer chip that uses lasers to transmit data at 100 times the speed of current communications equipment.[5] In two dimensions it includes the manufacture of carbon nanotubes only one nanometer in diameter that may be eventually reach several centimeters in length. In three dimensions it encompasses the manufacture of small particles no more than a few nanometers in any dimension that might be used as an ingredient in sunscreens or to deliver medicine to a specific type of cell in the body.

In a more general context nanotechnology can be seen as just the current stage of a long-term ability to understand and manipulate matter at ever smaller scales as time goes by. Over the last century, physicists and biologists have developed a much more detailed understanding of matter at finer and finer levels. At the same time, engineers have gradually acquired the ability to reliably manipulate material to increasingly finer degrees of precision. Although we have long known much of what happens at the nanolevel, the levels of knowledge implied by; 1) knowing about the existence of atoms, 2) actually seeing them, 3) manipulating them, and 4) truly understanding how they work, are dramatically different. The last two stages especially open up significant new technological abilities. At the nanolevel technology has just recently reached these stages.

Two examples indicate the significance of current research. Biologists have known about the basic building blocks of DNA since 1953, but until recently did not know the exact DNA sequence of a human being. This occurred in the last decade. Viruses were another mystery, but now scientists not only know the DNA sequence, they have used this knowledge to build a virus that assembles a battery.[6] As a second example, rather than just being able to see individual atoms with an electron microscope, scientists can now place a 20-nm indentation on a piece of material, creating a data

[3] *The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel*, President's Council of Advisors on Science and Technology, Washington D.C., May 2005, p. 7.
[4] *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*, Royal Society and The Royal Academy of Engineering, UK, July 2004, p. 5.
[5] Markoff, John, "A Chip That Can Move Data at the Speed of Laser Light," *New York Times*, September, 18, 2006, p. C1.
[6] "Powerful Batteries That Assemble Themselves." *Technology Review*, available at http//:www.technologyreview.com/printer_friendly_article.aspx?id=17553.

storage system with the capacity to store 25 million printed textbook pages on a square inch chip.[7]

What makes work at the nanolevel more than just a natural progression of earlier work at the micro and macro levels of matter? For one thing the basic building blocks of matter and life occur at the nanolevel. Molecular chemistry, genetic reproduction, cellular processes, and the current frontier of electronics all occur on the nanolevel. Understanding how these processes work and, more importantly, being able to reliably manipulate events at this level in order to get specific outcomes, opens up the possibility of significant new advances in a wide variety of fields including electronics, medicine, and material sciences.

Second, the nanolevel represents the overlap between traditional physics and quantum mechanics. At this scale the physical, chemical, and biological properties of materials differ in fundamental ways from the properties of either individual atoms or bulk matter.[8] This makes the prediction of cause and effect relationships much more difficult and introduces phenomena such as quantum tunneling, superposition, and entanglement. As a result, material at the nanoscale can exhibit surprising characteristics that are not evident at large scales. For example:

- Collections of gold particles can appear orange, purple, red, or greenish, depending upon the specific size of the particles making up the sample.[9]
- Carbon atoms in the form of a nanotube exhibit tensile strengths 100 times that of steel and can be either metallic or semiconducting depending on their configuration.
- Titanium dioxide and zinc oxide, common ingredients in sun screen, both appear white when made of macro particles. But when the particles are ground to the nanoscale, they appear translucent.

The Progression of Nanotechnology

Why now? If it seems that nanotechnology has begun to blossom in the last ten years, this is largely due to the development of new instruments that allow researchers to observe and manipulate matter at the nanolevel. Technologies such as scanning tunneling microscopy, magnetic force microscopy, and electron microscopy allow scientists to observe events at the atomic level. At the same time, economic pressures in the electronics industry have forced the development of new lithographic techniques that continue the steady reduction in feature size and cost. Just as Galileo's knowledge was limited by the technology of his day, until recently a lack of good instrumentation prevented scientists from gaining more knowledge of the nanoscale. As better

[7] Richard Booker and Earl Boysen, *Nanotechnology for Dummies,* Wiley Publishing Inc., (2005) pp. 142-44.
[8] The National Nanotechnology Initiative Strategic Plan, National Science and Technology Council, Washington D.C., December 2004, p. i.
[9] Mark Ratner and Daniel Ratner, *Nanotechnology: A Gentle Introduction to the Next Big Idea,* Prentice Hall (2003) p. 13.

instrumentation for observing, manipulating and measuring events at this scale are developed, further advances in our understanding and ability will occur.

One leader in nanotechnology policy has identified four distinct generations in the development of nanotechnology products, to which we can add a possible fifth:[10]

Passive Nanostructures (2000-2005)

During the first period products will take advantage of the passive properties of nanomaterials, including nanotubes and nanolayers. For example, titanium dioxide is often used in sunscreens because it absorbs and reflects ultraviolet light. When broken down into nanoparticles it becomes transparent to visible light, eliminating the white cream appearance associated with traditional sunscreens. Carbon nanotubes are much stronger than steel but only a fraction of the weight. Tennis rackets containing them promise to deliver greater stiffness without additional weight. As a third example, yarn that is coated with a nanolayer of material can be woven into stain-resistant clothing. Each of these products takes advantage of the unique property of a material when it is manufactured at a nanoscale. However, in each case the nanomaterial itself remains static once it is encapsulated into the product.

Active Nanostructures (2005-2010)

Active nanostructures change their state during use, responding in predicable ways to the environment around them. Nanoparticles might seek out cancer cells and then release an attached drug. A nanoelectromechancial device embedded into construction material could sense when the material is under strain and release an epoxy that repairs any rupture. Or a layer of nanomaterial might respond to the presence of sunlight by emitting an electrical charge to power an appliance. Products in this phase require a greater understanding of how the structure of a nanomaterial determines its properties and a corresponding ability to design unique materials. They also raise more advanced manufacturing and deployment challenges.

Systems of Nanosystems (2010-2015)

In this stage assemblies of nanotools work together to achieve a final goal. A key challenge is to get the main components to work together within a network, possibly exchanging information in the process. Proteins or viruses might assemble small batteries. Nanostructures could self-assemble into a lattice on which bone or other tissues could grow. Smart dust strewn over an area could sense the presence of human beings and communicate their location. Small nanoelectromechancial devices could search out cancer cells and turn off their reproductive capacity. At this stage significant advancements in robotics, biotechnology, and new generation information technology will begin to appear in products.

[10] M.C. Roco, "Nanoscale Science and Engineering: Unifying and Transforming Tools" *AIChE Journal* Vol. 50, No. 5, pp. 895-6. Until recently, Dr. Roco chaired the U.S. National Science Technology Council's Subcommittee on Nanoscale Science, Engineering and Technology.

Molecular Nanosystems (2015-2020)

This stage involves the intelligent design of molecular and atomic devices, leading to "unprecedented understanding and control over the basic building blocks of all natural and man-made things."[11] Although the line between this stage and the last blurs, what seems to distinguish products introduced here is that matter is crafted at the molecular and even atomic level to take advantage of the specific nanoscale properties of different elements. Research will occur on the interaction between light and matter, the machine-human interface, and atomic manipulation to design molecules. Among the examples that Dr. Roco foresees are "multifunctional molecules, catalysts for synthesis and controlling of engineered nanostructures, subcellular interventions, and biomimetics for complex system dynamics and control."[12] Since the path from initial discovery to product application takes 10-12 years,[13] the initial scientific foundations for these technologies are already starting to emerge from laboratories. At this stage a single product will integrate a wide variety of capacities including independent power generation, information processing and communication, and mechanical operation. Its manufacture implies the ability to rearrange the basic building blocks of matter and life to accomplish specific purposes. Nanoproducts regularly applied to a field might search out and transform hazardous materials and mix a specified amount of oxygen into the soil. Nanodevices could roam the body, fixing the DNA of damaged cells, monitoring vital conditions and displaying data in a readable form on skin cells in a form similar to a tattoo. Computers might operate by reading the brain waves of the operator.

The Singularity (2020 and beyond)

Every exponential curve eventually reaches a point where the growth rate becomes almost infinite. This point is often called the Singularity. If technology continues to advance at exponential rates, what happens after 2020? Technology is likely to continue, but at this stage some observers forecast a period at which scientific advances aggressively assume their own momentum and accelerate at unprecedented levels, enabling products that today seem like science fiction. Beyond the Singularity, human society is incomparably different from what it is today. Several assumptions seem to drive predictions of a Singularity[14]. The first is that continued material demands and competitive pressures will continue to drive technology forward. Second, at some point artificial intelligence advances to a point where computers enhance and accelerate scientific discovery and technological change. In other words, intelligent machines start to produce discoveries that are too complex for humans. Finally, there is an assumption that solutions to most of today's problems including material scarcity, human health, and

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[11] M.C. Roco, "International Perspective on Government Nanotechnology Funding in 2005," *Journal of Nanoparticle Research*, Vol. 7, No. 6, p. 707.
[12] M.C. Roco, "Nanoscale Science and Engineering: Unifying and Transforming Tools" *AIChE Journal* Vol. 50, No. 5, p. 896.
[13] *Id.*
[14] Ray Kurzweil, *The Singularity is Near: When Humans Transcend Biology*, Viking Press (2005).

environmental degradation can be solved by technology, if not by us, then by the computers we eventually develop.

Whether or not one believes in the Singularity, it is difficult to overestimate nanotechnology's likely implications for society. For one thing, advances in just the last five years have proceeded much faster than even the best experts had predicted. Looking forward, science is likely to continue outrunning expectations, at least in the medium-term. Although science may advance rapidly, technology and daily life are likely to change at a much slower pace for several reasons. First, it takes time for scientific discoveries to become embedded into new products, especially when the market for those products is uncertain. Second, both individuals and institutions can exhibit a great deal of resistance to change. Because new technology often requires significant organizational change and cost in order to have its full effect, this can delay the social impact of new discoveries. For example, computer technology did not have a noticeable effect on economic productivity until it became widely integrated into business offices and, ultimately, business processes. It took firms over a decade to go from replacing the typewriters in their office pools to rearranging their entire supply chains to take advantage of the Internet. Although some firms adopted new technologies rapidly, others, lagged far behind.

The Structure of Nanotechnology

Nanotechnology is distinguished by its interdisciplinary nature. For one thing, investigations at the nanolevel are occurring in a variety of academic fields. More important, the most advanced research and product development increasingly requires knowledge of disciplines that, until now, operated largely independently. These areas include:

- *Physics* — The construction of specific molecules is governed by the physical forces between the individual atoms composing them. Nanotechnology will involve the continued design of novel molecules for specific purposes. However, the laws of physics will continue to govern which atoms will interact with each other and in what way. In addition, researchers need to understand how quantum physics affects the behavior of matter below a certain scale.

- *Chemistry* — The interaction of different molecules is governed by chemical forces. Nanotechnology will involve the controlled interaction of different molecules, often in solution. Understanding how different materials interact with each other is a crucial part of designing new nanomaterials to achieve a given purpose.

- *Biology* — A major focus of nanotechnology is the creation of small devices capable of processing information and performing tasks on the nanoscale. The process by which information encoded in DNA is used to build proteins, which then go on to perform complex tasks including the building of more complex structures, offers one possible template. A better understanding of how biological systems work at the lowest level may allow future scientists to use similar processes to accomplish new purposes. It is also a vital part of all research into medical applications.

- *Computer Science* — Moore's Law and its corollaries, the phenomena whereby the price performance, speed, and capacity of almost every component of the computer and communications industry has improved exponentially over the last several decades, has been accompanied by steady miniaturization. Continued decreases in transistor size face physical barriers including heat dissipation and electron tunneling that require new technologies to get around. In addition, a major issue for the use of any nanodevices will be the need to exchange information with them. Finally, scientific advances will require the ability to manage increasingly large amounts of information collected from a large network of sensors.[15]

- *Electrical Engineering* — To operate independently, nanodevices will need a steady supply of power. Moving power into and out of devices at that scale represents a unique challenge. Within the field of information technology, control of electric signals is also vital to transistor switches and memory storage. A great deal of research is also going into developing nanotechnologies that can generate and manage power more efficiently.

- *Mechanical Engineering* — Even at the nanolevel issues such as load bearing, wear, material fatigue, and lubrication still apply. Detailed knowledge of how to actually build devices that do what we want them to do with an acceptable level of confidence will be a critical component of future research.

Unfortunately, most of academia and the research community do not facilitate this type of multidisciplinary research. Work often tends to be compartmentalized into disciplines and subdisciplines with their own vocabularies. Research proposals are evaluated by experts within one area who neither understand nor appreciate developments in other fields. Young people coming into a field are usually rewarded for extending existing lines of research and take a risk if they try to look at the unexamined gaps between academic fields.

Yet in nanotechnology most of the great possibilities are precisely in these gaps. In 2002 the National Academy of Sciences listed several important areas for investment in nanotechnology. All of them involved interdisciplinary research.[16] The National

[15] *See*, Microsoft Corporation, *Toward 2020 Science*, available at http://research.microsoft.com/towards2020science/downloads/T2020S_ReportA4.pdf

[16] National Academy of Sciences, *Small Wonders, Endless Frontiers,* Washington D.C., 2002, pp. 36-45.

Science Foundation is trying to encourage such research by awarding grants specifically for it.

With so many sciences having input into nanotechnology research, it is only natural that the results of this research are expected to have a significant impact on a similarly broad range of applications. Ray Kurzwiel labels these applications genetics, nanotechnology, and robotics (GNR),[17] to which one can add information technology (GRIN).[18] The National Nanotechnology Initiative has adopted the similar classification of nanotechnology, biotechnology, information technology, and cognitive science (NBIC).[19]

These sciences interrelate in a number of ways:

Nanotechnology — Nanotechnology often refers to research in a wide number of fields including the other three listed below. But in its limited sense it refers to the ability to observe and manipulate matter at the level of the basic molecules that govern genetics, cell biology, chemical composition, and the current and future generations of electronics. Researchers can then apply this ability to advance science in other fields. The broader definition of nanotechnology applies throughout most of this paper, but it is worth remembering that advances in other sciences depend on continued improvements in the ability to observe, understand, and control matter at the nanolevel. This in turn will require more accurate and less expensive instrumentation and better techniques for producing large numbers of nanodevices.

Biotechnology (Genetics) — Nanotechnology promises an increased understanding and manipulation of the basic building blocks underlying all living matter. The basic theory of genetic inheritance has been known for some time. But biologists do not fully understand the details of how life goes from a single fertilized egg with a full set of chromosomes to a living animal. Questions exist on exactly how the information encoded in DNA is transcribed, the role of proteins, the internal workings of the cell and many other areas. Basically DNA consists of a long string of four molecules; adenine, thymine, guanine, and cytosine. Since these molecules are read off in units of three (called codons), there are 64 possible combinations. Each combination corresponds to one of 20 amino acids. The amino acids in turn form proteins that fold in unique three dimensional ways and perform many of the functions within individuals cells. On a basic level, research is allowing us to tease out the genetic basis for specific diseases and in the future may reliably allow us to correct harmful mutations. But what would a full understanding of the genetic process give us? Could we develop DNA that uses a fifth and sixth molecule? Could the existing process be reprogrammed to code for more than

[17] Ray Kurzweil, *The Singularity is Near: When Humans Transcend Biology*, Viking Press (2005), pp. 205-98.
[18] Joel Garreau, *Radical Evolution: The Promise and Peril of Enhancing Our Minds, Our Bodies – and What it Means to Be Human*, Doubleday (2005).
[19] Mihail C. Roco, "The Emergence and Policy Implications of Converging New Technologies," In William Sims Bainbridge and Mihail C. Roco (Eds.), *Managing Nano-Bio-Info-Cogno Innovations: Converging Technologies in Society*, Springer (2006), pp. 8-22.

20 amino acids? To what extent is it possible to create brand new proteins that perform unique functions?

A better understanding of biological processes is obviously needed in order to deliver the health benefits that nanotechnology promises. But it is also important for many reasons outside of biology. Those used to traditional manufacturing techniques may at first have difficulty with the concept of building a product up from the molecular level. Biology offers a template for doing so. A single fertilized egg in the womb eventually becomes a human being; a system of incredible complexity from a simple set of instructions 2.5 nm in diameter. Scientists are hopeful that similar processes can be used to produce a range of other products.

Information Technology — Progress in information processing has depended on the continued application of Moore's law, which predicts a regular doubling of the number of transistors that can be placed on a computer chip. This produced exponential improvements in computing speed and price performance. Current computer technology is based on the Complementary Metal Oxide Semiconductor (CMOS). The present generation of computer chips already depends on features as small as 70 nanometers. Foreseeable advances in nanotechnology are likely to extend CMOS technology out to 2015. However, at transistor densities beyond that several problems start to arise. One is the dramatic escalation in the cost of a new fabrication plant to manufacture the chips. These costs must be amortized over the cost of the transistors, keeping them expensive. Second, it becomes increasingly difficult to dissipate the heat caused by the logic devices. Lastly, at such small distances, electrons increasingly tunnel between materials rather than going through the paths programmed for them. As a result of these constraints, any continuation of Moore's Law much beyond 2015 is likely to require the development of one or more new technologies.

Future advances will also bring us closer to a world of free memory, ubiquitous data collection, massive serial processing of data using sophisticated software, and lightening-fast, always-on transmission. What happens when almost all information is theoretically available to everyone all the time?

Cognitive Sciences (Robotics) — Continued advances in computer science combined with a much better understanding of how the human brain works should allow researchers to develop software capable of duplicating and even improving on many aspects of human intelligence. Although progress in Artificial Intelligence has lagged the expectations of many of its strongest proponents, specialized software continues to advance at a steady rate. Expert software now outperforms the best humans in a variety of tasks simply because it has instantaneous access to a vast store of information that it can quickly process. In addition, researchers continue to develop a much better understanding of how individual sections of the brain work to perform specific tasks. As processing power continues to get cheaper, more and more of it will be applied to individual problems.

Does Nanotechnology Represent a Danger to Society?

Few people would doubt that technology has brought great benefits to human society. Even those who are often the most vocal in shunning it are usually quick to adopt those aspects, such as better health and communication, which suit their purposes. In spite of these benefits, society has a love/hate relationship with new advances. This is partially because new technology always creates new economic possibilities, which upset those benefiting from the status quo. Luddites destroyed the first weaving machines because they threatened their existing jobs. The protesters gave little thought to the masses of people who might, for the first time, be able to purchase a second set of clothes at an affordable price. Perhaps deeper is an uneasiness with the uncertainty of where technology might ultimately take us. Is there such as thing as too much progress? Who exactly will benefit? What possible problems lurk and how will we deal with them? What are the social implications? These and other unanswerable questions have often been used as excuses to forego technology's benefits in favor of the comfort of today's problems.

Nanotechnology has generated similar concerns. In perhaps the best known example, Bill Joy, former chief technology officer for Sun Microsystems, wrote an article in which he seriously questioned the wisdom of going forward with current research.[20] Mr. Joy's fears revolved around three possible threats:

- Nanodevices that get out of control. The minuteness of the nanoscale and the vast number of nanoorganisms or devices that are needed to be effective at a macroscale implies a certain loss of control once they are released into the environment. We will have created a lot of them and we will have trouble knowing exactly where they are or what they are doing. Some have expressed the fear that self-replicating nanobots might multiply out of control, eventually consuming all matter and covering the world in a "grey goo." This threat, first raised by Eric Drexler in his book *Engines of Creation* and later the subject of a novel by Michael Crichton has since been widely discredited by most scientists. Beyond the issue that no one now knows how to make self-replicating machines, there are serious questions about how such a process could sustain itself without any clear source of energy. Even Eric Drexler has testified that the grey goo scenario is the wrong issue to focus on.[21]

- The rapid proliferation of the knowledge and equipment needed to create new biological life forms. Mr. Joy is especially concerned that this knowledge intentionally will be used to create and release new pathogens. Unlike nuclear technology, the capacity to create biological weapons of mass destruction requires far less capital investment and is much easier to conceal. This concern is one that will have to be addressed. However, it is very hard to see how society can totally avoid this risk without at the

[20] Bill Joy, "The Future Doesn't Need Us" *Wired*, April 2000.
[21] The Royal Society and Royal Academy of Engineering, *Nanoscience and Nanotechnologies: Opportunities and Uncertainties,* RS Policy Document 19/04, July 2004, p. 109.

same time giving up on technologies that promise to cure cancer, correct genetic defects, and create new organisms capable of cleaning up toxic chemicals.[22]

- Mr. Joy's final concern was that advances in information technology and artificial intelligence will eventually create an intelligence superior to ours, which may not act solely in our interest. Again Mr. Joy is far more likely to be right about the direction of technology than about its evil effects. The history of technology is that its benefits have vastly outweighed its dangers and that society has eventually found ways to manage even the worst dangers, often using further advances in technology. As with biotechnology, it is hard to see how society could avoid the possibility of running this danger without at the same time giving up all the benefits that greater automation promises.

Some applications will be harmful and good science is needed to detect and respond to these harms as early as possible. Any broad technology brings both benefits and dangers. As discussed below, certain applications of nanotechnology do present serious environmental and health issues. These applications will have to be monitored and, if the harm outweighs the benefits, curtailed. But such decisions should be made on the basis of sound science, not emotional appeals about the dangers of the unknown. And government policy should reflect the fact that on the whole nanotechnology is expected to bring large net benefits to society and should be encouraged.

Yet, the fear of technology displacing humans runs deep in the human psyche and explains events as diverse as the persecution of Copernicus and Galileo, the Salem Witch Trials, and the continued popularity of Mary Shelley's *Frankenstein* over a century after it was first written. There is also a strong tradition of Luddite opposition to any technology that threatens the existing market of any special interest. Presently, universities, optometrists, realtors, car dealerships, and others are all scrambling to protect themselves from competition enabled by the Internet. The special interests that seek these protections almost always try to justify them as efforts to protect consumers or society.

Any application of technology that causes large costs quickly draws society's attention to it and the costs it imposes provide a strong incentive to correct them. There are therefore reasons to think that, with careful monitoring any product that actually causes severe harm to the environment or health can be removed relatively quickly. Although there are legitimate issues about nanotechnology's effects, any proper discussion of regulation should explicitly acknowledge the danger of letting special interests on either side hijack the process by using legitimate concerns as a pretext for barriers whose main purpose is really to satisfy the interests of narrow groups or to fan unfounded fears. Regulation should also explicitly weigh the risk of inhibiting beneficial uses against the benefit of preventing harmful applications.

[22] *See also*, Mark Williams, "The Knowledge," *Technology Review*, (March/April 2006), p. 44.

Government Policy Toward Nanotechnology

We should view government policy in this context. As explained above, nanotechnology is still in its early stages. Many of the most valuable commercial applications are decades away and require continued advances in basic and applied science. As a result, government funding still constitutes a large proportion of total spending on research and development. Within the United States, this spending is guided by the National Nanotechnology Initiative (NNI).[23] The NNI coordinates the policy of 25 government agencies, including 13 that have budgets for nanotechnology research and development.[24] It has set up an infrastructure of over 35 institutions across the country to conduct basic research and facilitate the transfer of technology to the private sector.

The NNI's strategic plan sets out four main goals:[25]

- Maintain a world-class research and development program to exploit the full potential of nanotechnology.
- Facilitate the transfer of nanotechnology into products for economic growth, jobs, and other public benefits.
- Develop educational resources, a skilled workforce, and the supporting infrastructure to advance nanotechnology.
- Support responsible development of nanotechnology.

The NNI is clearly geared toward developing the technology on a broad front, correctly seeing it as the source of tremendous benefits to society. Its mission is not to see whether we should go forward with research and development. It is to go forth boldly, while trying to discover and deal with possible risks.

Despite the fears expressed by Bill Joy, there is relatively little serious debate among policymakers over possible long-term existential threats to mankind. The main topics of discussion are the possible health risks associated with nanoparticles and the need for greater public participation in the development of the technology. Each of these topics is worthy of discussion, but their implications for public policy are much more nuanced than many of their proponents realize. Neither is likely to seriously affect the broad development of these new technologies although they could improve the net benefits that society realizes from them.

A number of concerns have been raised about the effect nanoparticles might have on human health. Precisely because of their small size, there is some fear that they might unintentionally penetrate the normal biological barriers that protect human health. For

[23] Significant legislation governing the NNI includes the 21st Century Nanotechnology Research and Development Act (P.L. 108-153). Interagency coordination is managed by the Nanoscale Science, Engineering, and Technology Subcommittee within the National Science and Technology Council.
[24] For a good description of the NNI, see, National Science and Technology Council, *The National Nanotechnology Initiative: Supplement to the President's 2007 Budget*, Washington D.C., July 2006. Available at http://www.nano.gov/NNI_07Budget.pdf.
[25] National Science and Technology Council, *The National Nanotechnology Initiative, Strategic Plan,* Washington D.C., December 2004. Available at: http://www.nano.gov/NNI_Strategic_Plan_2004.pdf.

instance, could a certain particle penetrate human skin, from there cross tissue protecting the brain from foreign chemicals and finally migrate through cell walls to interfere with cell function? Note that in the future, some particles might be specifically designed to do exactly that in order to deliver medication to patients with brain tumors. The concern here is with unintentional exposures. The human body has already evolved defenses against constant exposure to a large variety of nanoparticles, including soot and bacteria. However, in the future many nanoparticles will have novel structures that neither our immune systems nor the environment have ever come into contact with before.

Several animal studies show that certain exposures can lead to health problems, but it is far from clear whether the results have much relevance to the expected exposures humans will face. The central fear is that an engineered particle that is widely used could turn out to be like asbestos or PCBs and have serious long-term health consequences that are recognized only after thousands of people have suffered or large costs have been incurred. In fact, some scientists claim that carbon nanotubes exhibit properties similar to asbestos fibers at the nanoscale.

A recent report by the National Academy of Sciences concluded that: "for now there is very little information and data on, or analysis of, [environmental health and safety] impacts related to nanotechnology" and that "the body of published research addressing the toxicological and environmental effects of engineered nanomaterials is still relatively small."[26] As a result, there has been a widespread call for more greater federal action to address possible health concerns before they arise. Some researchers have called for increasing the government's power to regulate nanoproducts, arguing that existing laws such as the Food, Drug and Cosmetic Act, the Toxic Substances Control Act, and the Occupational Safety and Health Act are inadequate to deal with potential problems.[27] Others have called for significant increases in research on the health effects of nanoparticles and a beeter prioritization of federal spending.[28]

A better understanding of how specific particles affect human health would be enormously valuable. But realizing this will not be as easy as many people would like. First, much knowledge will have to wait for the development of better equipment and facilities capable of measuring quantities and events on such a small scale. The National Academy of Sciences concluded that: "[t]he ability to carry out comprehensive EHS R&D requires that techniques and instrumentation for characterization and measurement be developed that will enable determination of the exact composition of a nanomaterial in a substance or product, as well as the physicochemical properties of specific

[26] *A Matter of Size: Triennial Review of the National Nanotechnology Initiative*, National Academy of Sciences, Washington D.C. 2006, p. 78.
[27] *See*, J. Clarence Davies, *Managing the Effects of Nanotechnology*, Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies, Washington D.C. Available at: http://nanotechproject.org/index.php?s=reports.
[28] See, Andrew D. Maynard, *Nanotechnology: A Research Strategy for Addressing Risk*, Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies, Washington D.C., July 2006. Available at: http://nanotechproject.org/index.php?s=reports.

nanomaterials."[29] Equipment to accurately measure and observe events at the nanoscale is still relatively primitive compared to where it is likely to be in 10-20 years.

Second, spending more money on research does not necessarily mean that the research will be worth the money. Proponents of additional spending are right to point out that, given the relatively small amount currently being spent, the marginal benefits from spending are likely to be high, at least for the next few years. The National Academy of Sciences recommended increasing research on the environmental, health and safety effects of nanotechnology.[30] Although the Academy did not cite a figure, others have called for spending $50 million to $200 million annually.[31] Although this would represent a large increase from the approximately $35 million that the NNI claims to devote to the area now, if properly allocated through peer-reviewed grants by agencies such as the National Science Foundation, such a sum should produce large benefits for several reasons. First, once the results are published they will provide a good base for the private sector to build off of in evaluating the safety of proposed products. Second, the studies should further the knowledge of how engineered nanoproducts interact with biological systems at the cellular level. In addition to making it easier to avoid the production of harmful materials, this general knowledge should make it easier to engineer nanomaterials that accomplish beneficial health purposes. To a large extent, EHS research is a natural complement to efforts to use nanotechnology to combat diseases such as cancer.

But rapid increases in funding do not automatically guarantee rapid increases in results. One important issue is the degree to which agencies should pursue a central list of research priorities. At present, although agencies coordinate through the NNI, each agency retains full control over its own budget decisions and sets its own priorities for research. The National Academy of Sciences concluded that "the NNI is successfully establishing R&D programs with wider impact than could have been expected from separate agency funding without coordination….The committee believes that federal agencies have been motivated by their participation in NNI activities to establish priorities, coordinate programs, and leverage resources to a degree that has proved very effective."[32]

Although centralization might produce a consistent list of priorities, it does not always produce the best one. If centralization might steer funding toward important areas that the agencies might normally view as being outside their narrow areas of concern, it might also fail to fund some areas of research that are central to an agency's mission. Centralized priorities are only as good as the process used to establish and implement

[29] *A Matter of Size: Triennial Review of the National Nanotechnology Initiative*, National Academy of Sciences, 2006, p. 80.
[30] *Id.* p. 92.
[31] See, Andrew D. Maynard, *Nanotechnology: A Research Strategy for Addressing Risk*, Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies, July 2006; Testimony of Matthew M. Nordon, President, Lux Research Inc., September 21, 2006, U.S. House of Representatives Committee on Science.
[32] *A Matter of Size: Triennial Review of the National Nanotechnology Initiative*, National Academy of Sciences, 2006, p. 6.

them. Given that the NNI is presently based purely on collaboration, the best alternative would probably be to give the NNI a significant portion of independent budgetary authority that it could use to fund research in areas that fall in between or overlap the interests of the separate agencies. An independent budget would also give the NNI greater weight in guiding the agencies toward consistent progress on developing a coordinated nanotechnology policy but still leave the latter free to pursue their own mandates.

It is also very clear that health research must be better coordinated with the private sector and government agencies at the state and international levels. Experiments done in one part of the world have immediate relevance to all other areas and there is great benefit in avoiding duplication and spreading research findings widely. The benefits of coordinating research among domestic and international laboratories are significant.

A final issue concerns the obligations that private companies should face in ensuring the safety of the products they sell in the market. In many cases, such as cosmetics, these products face very little regulatory scrutiny prior to reaching consumers. The combined lack of testing and oversight has led at least one organization to call for a moratorium on the further commercial release of personal care products that contain engineered nanomaterials and the withdrawal of products currently on the market.[33] The general issue of risk is discussed in greater detail below. But one legitimate concern is a lack of information on the amount and type of testing that testing companies perform in order to ensure that their products are safe. Under current law, companies are not required to disclose the results of any safety testing and many companies consider such research proprietary.

The debate on the safety of using nanotechnology would be improved if three changes were made governing the use of nanotechnology in products. First, the use of nanotechnology should be clearly labeled on products so that consumers can make an informed choice about whether to use a particular product. At present, manufacturers are split on the marketing value of nanotechnology. Some tout it in their advertising even if their product does not technically contain nanoparticles, on the theory that consumers are attracted to new technology. Others, fearing a consumer backlash if consumers develop a negative view of nanotechnology, omit any mention of the word. Clearer labeling of exactly what ingredients are used and of the particle size would give consumers accurate information and reduce the possibility of a sudden backlash if there is a problem with one or more specific products. Consumers ought to have the ability to make independent judgments about whether to purchase products with nanoparticles.

Second, private companies should be required to disclose to the Food and Drug Administration the results of any safety testing that they conduct and the FDA should immediately publicize any results that show a clear negative health effect. Companies would then probably find it in their interest to publicize neutral or positive findings. Disclosure of test results does have important strategic implications for companies that

[33] *Nanomaterials, Sunscreens, and Cosmetics: Small Ingredients Big Risks,* Friends of the Earth, May 2006.

compete for market share. But, since most safety testing will be done by the private sector, members of the public should have the right to see what steps companies are taking to protect their health. This would also ensure that the debate over safety occurs in public with full information. While this might subject companies to some discomfort in the short-term, it will make it much more difficult for opponents of the technology to use public distrust to exploit any negative stories. Congress could encourage additional safety testing by making it easier for companies to collaborate on precompetitive research into the environmental, health and safety impact of nanomaterials.

Additional efforts to identify the environmental, health and safety risks of nanoparticles will bring clear benefits. But the need to conduct these studies should not be used to prevent the introduction of new products. Science and technology have always involved a leap into the unknown, bringing with it an assumption of unforeseen risks. Opponents of technology can always point to examples of innovation gone bad such as asbestosis, DDT, PCBs. But their analysis of this risk omits three important facts. First, each of these products brought with them significant benefits which, at least for a while, could not be duplicated by other products. Indeed DDT has recently been reapproved for limited use to combat malaria. Second, even if the total cost of these products outweighed their benefits, the former were unnecessarily increased by a lack of full disclosure about research into their health effects. That is why an open debate about EHS testing is so important. It allows society to improve the cost/benefit equation of any given product. Third, and by far the most important, any testing policy that significantly delayed the use of these products might have also delayed the use of thousands of other products that did not prove to pose significant health risks. This would have had major impacts on economic growth and consumer welfare. Any policy that tries to stop harmful products from entering the market must try to do so without significantly delaying the vast majority of products that bring net benefits.

One environmental group has made clear its position on nanotechnology. It calls for a moratorium on all products containing nanomaterials. In their words: "We believe that ethical concerns and the likely far-reaching socio-economic impacts of nanotechnology, must be addressed alongside concerns over nanotoxicity before the commercialization of nanotechnology proceeds." One of the many criteria that they require to be met before nanomaterials can be commercially released is that "safety assessments are based on the precautionary principle and the onus is on proponents to prove safety, rather than relying on an assumption of safety.[34]

Rather than being an impartial look at the possible health risks of using nanoparticles in cosmetic products, the report is a biased swipe against a broad category of consumer products. In the case of sunscreens there is no discussion of the possible benefits that might occur if more people either use more sunscreen or find its use more enjoyable because standard ingredients such as zinc oxide and titanium dioxide appear clear rather than white at the nanoscale. This sort of possible benefit is simply assumed not to be important. Having established that the benefits are zero, the report then looks at the risks. Here its discussion is similarly one-sided. Although it cites the 2004 report of

[34] *Id.*, p. 17.

the Royal Society at least 14 times, it never mentions the report's discussion of the regulatory approval for titanium dioxide. Nor does it point out that the Royal Society specifically found that a moratorium on nanotechnology was not justified.

Of course, it is unclear how the standard advocated by Friends of the Earth could ever be met. Few products come with an absolute guarantee of safety for all portions of the population. Under this standard it would not be enough if a product's cost/benefit ratio was positive or even very high. The question would be whether the product imposed any risks to society at all. And if there was even the possibility of a risk (and there would almost always be at least the possibility) then the product could be rejected. Proponents of growth should always remember that there is a certain section of the population that argues against the introduction of peanuts because exposure can be deadly to those with a strong allergic reaction to them. Similar arguments can and will be made against nanotechnologies even when an impartial cost/benefit evaluation shows that the technology will probably bring net benefits to society.

The requirement to address "the far-reaching socio-economic impacts" also imposes an almost insuperable barrier. First, many of these impacts are unknowable because they depend on a variety of other events in the future. Widely used technologies do not impact society as single items. They combine to constitute a web of technology that changes the entire social system. It is usually meaningless to pick out one possible application of the technology and evaluate it apart from all the complementary and competing technologies that affect its impact on society. Second, many of the most significant impacts will occur because nanotechnology brings with it large benefits and therefore becomes infused into a wide variety of products in many industries. Most of those who are negatively affected by it will be so because the technology opens up new production, distribution and profit opportunities. They will quickly use arguments against the technology to seek competitive protection.

There is a widespread desire to avoid repeating the mistakes of biotechnology, a technology whose advance has been substantially slowed by political opposition that has little scientific basis. But it is not really clear what the mistakes of biotechnology are. No human deaths can be attributed to genetically modified organisms. Nor has any product of biotechnology ever resulted in significant environmental harm. The potential health and environmental benefits of biocrops in the form of reduced use of pesticides, fertilizer, and fuel and improved vitamin delivery are totally discounted in favor of vague warnings against Frankenfood. One might wish that companies like Monsanto had been more open about their research and intentions, but this research surely would have been used against them by environmental groups who intentionally distort the debate by exaggerating any dangers and denying any benefits. It is far from certain that better studies and more open debate would have produced a more reasoned policy.

Much of the reaction against nanotechnology is based solely on the fact that even if it has benefits, these benefits will change society in substantial ways. This is why opponents often mention the need to look at "socio-economic effects". Similar arguments are being used today against the expansion of the Internet. Realtors have argued that home searches done over the Internet are not really the same as those done by a licensed professional and that the industry therefore should not have to open up its listing services to discount brokers. Optometrists have argued that contact lenses purchased over the Internet are not really as safe as those that they sell and that therefore they should be allowed to write prescriptions for brands that promise not to make their products available to Web stores. Of course, in neither of these arguments is there room for the consumer to determine what actually does or does not benefit him. Rather, the strategy is for the incumbents to make the decision for the individual. Had the development of the World Wide Web waited for a full understanding of its "socio-economic effects" it would probably not exist today.

In this context it is worth discussing what role the public should play in guiding the progress of nanotechnology. The NNI has defined seven Program Component Areas under which it groups related projects and activities. One of the Program Component Areas is devoted to the societal dimensions of nanotechnology. Within this category the NNI intends to foster the following activities:[35]

- Research on the environmental, health and safety impacts of nanotechnology;
- Educational activities including the development for materials for schools, technical training and public outreach; and
- Research on the broad implications of nanotechnology, including social, economic, ethical, and legal implications.

This implies an intent to educate the public about the benefits (or costs) and progress of nanotechnology. Proponents of public education and EHS research frequently point to biotechnology as a lesson of why such efforts are needed. The belief is that after a very promising start, progress in biotechnology has been slowed, and in some cases even halted, due to a broad public reaction that is fueled by:

- Public health scares, although in most cases these had nothing to do with biotechnology. A good example is the damage caused by mad cow disease in England and the rest of Europe. Government delay and deception in dealing with this issue led to a significant decline in the public's confidence about the government's commitment to safety regulation, which opponents of biotechnology exploited.
- The lack of outreach and openness on the part of biotechnology companies such as Monsanto. These companies took the lack of public opposition for granted and did not respond rapidly to questions about the safety or economic benefits of their products.
- Lack of general public education about either the science or the economic benefits of genetically modified crops. This lack of knowledge provided little perspective with which to judge conflicting health claims. Since

[35] National Science and Technology Council, *The National Nanotechnology Initiative, Strategic Plan,* Washington D.C., December 2004. Available at: http://www.nano.gov/NNI_Strategic_Plan_2004.pdf.

consumers did not know of any benefits biotechnology might bring, they had little reason to miss them.

- A determined opposition by some environmental groups that were adamantly opposed to the use of genetically modified crops under any conditions, regardless of the science. These groups engaged in a determined campaign to convince the public that biotechnology represents a grave threat to the public health and the environment. They took legitimate questions and expanded them into worst case scenarios and then made those scenarios seem like a certainty if a complete ban was not enforced. They often used violence to enforce their beliefs and gain publicity for their cause.

It is hard to argue against public education. The public should have a voice in how public money is spent, and it should be an informed voice. Even within the NNI budget, allocations between theoretical research, medical applications, and EHS studies are subjects of legitimate debate.

But it is important to have a realistic view of what public engagement can accomplish. As we go forward, an increasing proportion of investment in nanotechnology will come from the private sector. As a result, government will gradually lose much its ability to shape the direction of in which the technology advances. Decisions will increasingly be made by a decentralized collection of international businesses, universities, consumers and investors. Any attempt to subject these decisions to a collective decision process in order to manage broad "socio-economic effects" is almost certain to do far more harm than good. But because the harm from overly stringent regulation will come mainly in the form of future beneficial technology that will be delayed or stopped altogether, it may not be immediately apparent. Government should, however, be involved in monitoring technological developments, identifying any specific environmental risks, holding manufacturers responsible for any harm that their products do cause, and, where appropriate, implementing carefully designed regulatory systems justified by careful cost/benefit analysis.

Nanotechnology must be allowed to proceed as other transforming technologies such as chemistry, steam power, and electricity have done. It must proceed at its own pace and in its own direction. Better dialogue and research can help society deal with specific problems as they become apparent. It can also address the inevitable economic dislocation that will affect specific markets. But policymakers should not fool themselves into thinking that a collective political process can guide the future any better than the market can. Regulations need to be based on clear cost/benefit calculations supported by scientific evidence. And regulations to address specific identified risks should not delay the advancement of a broad range of products that will surely bring large social and economic benefits.

The world in which our children live will surely be a different one. Whether it is a better one is largely up to them to decide. Continued technological advancement, including on the nanoscale, will not automatically make the world any fairer or safer, but it will increase the resources available to those who want to ensure that it is.

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