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NANOTECHNOLOGY

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14 May 2002

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DIRECTION DE LA RECHERCHE PARLEMENTAIRE

TABLE OF CONTENTS

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NANOTECHNOLOGY

INTRODUCTION

Nanotechnology has been hailed as having the potential to "change everything," having an enormous impact on virtually every scientific discipline and human technology. It has managed to capture the imagination of scientists and policy makers because it acts at the level where the basic electronic, chemical and biological properties of materials are defined.(1) Though it is still in its infancy, many hold that nanotechnology will be the driving force behind the next industrial revolution.(2) Governments around the world, including Canada, are devoting hundreds of millions of dollars annually in funding for nano research and development. Yet whether this much-hyped technology will manage to live up to its anticipated potential remains to be seen.

WHAT IS NANOTECHNOLOGY?

For a discipline with so much invested in it, nanotechnology is surprisingly difficult to define. Essentially, it refers to technology on the nanometre scale. A nanometre (1 nm) is a specific unit, one billionth of a metre (10^{-9} m); for comparison, one nanometre is equivalent to the width of 10 hydrogen atoms side by side.(3) The diameter of a red blood cell is

(1) P. Alivisatos, M. C. Roco and R. S. Williams, eds., "Introduction to Nanotechnology for Nonspecialists," in *Nanotechnology Research Directions: IWGN Workshop Report: Vision for Nanotechnology R&D in the Next Decade*, National Science and Technology Council, Committee on Technology, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), September 1999, pp. xxv-xxx.

(2) *Nano: the new buzzword in science and technology*, CORDIS Focus, no. 162, 20 November 2000, pp. 4-5.

(3) The prefix "nano" comes from the Greek for dwarf. According to the International System of Units (SI) it stands for one billionth of the base unit, or nine orders of magnitude lower, http://www.bipm.fr/enus/3_SI/si-prefixes.html.

about 800 nm, while that of a human hair is about 200,000 nm.[4] However, in recent years "nano" has become such a potent buzzword (some have cautioned that "the nano prefix could become as dangerous as the dotcom suffix")[5] that its exact meaning has become obscured. Some "nanotechnology" is not actually "nano," but rather "micro," a scale one thousand times larger.[6] Furthermore, some "nanotechnology" would be more appropriately named "nanoscience" as it is not really technology but rather basic research at the nano scale.[7]

Nonetheless, we can define nanotechnology as essentially the creation of useful materials, devices and systems through the manipulation of matter at the nanometre-length scale as well as the exploitation of novel properties and phenomena produced at that scale.[8] At the nanometre level, between the microscopic and macroscopic worlds, exists the "mesoscale," a world where matter is governed by a complex combination of both quantum mechanics and classical physics, making it a unique realm that we are only beginning to understand.[9] Because the nanoscale encompasses not only collections of individual atoms, but larger structures such as proteins and everything in between, research in this area draws on expertise from chemistry, physics, materials science and molecular biology, making it a truly multidisciplinary subject.

THE HISTORY OF NANOTECHNOLOGY

While science has pondered atoms for centuries, only recently have we acquired the necessary tools to examine them. In 1959, physicist Richard Feynman gave a lecture at the California Institute of Technology entitled "There's Plenty of Room at the Bottom." This now oft-quoted presentation would prove to be a defining moment in the history of nanotechnology. "I am not afraid," Feynman declared, "to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very *atoms*, all the way

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(4) "About Nanotechnology and Nanosciences," National Research Council of Canada, http://www.nrc.ca/nanotech/about_e.html.

(5) Ian Sample, "Small Visions, Grand Designs," *New Scientist*, 6 October 2001, pp. 31-37.

(6) Gary Stix, "Little Big Science," *Scientific American*, vol. 32, September 2001, pp. 32-37.

(7) *Ibid.,* p. 34.

(8) Alivisatos, Roco and Williams, p. xxv.

(9) Michael Roukes, "Plenty of Room, Indeed," *Scientific American*, vol. 32, September 2001, pp. 48-57.

down! What would happen if we could arrange the atoms one by one the way we want them?"[10] It would be another fifteen years before a researcher at the University of Tokyo would coin the term "nanotechnology," but Feynman's speech is generally regarded as the first serious scientific discussion of the subject.[11]

Richard Smalley and his team at Rice University made nanotechnology's most famous discovery in 1985. By vaporizing carbon and then letting it condense, the researchers found that the carbon atoms had arranged themselves in a highly stable crystal structure. The shape of the 60-atom structures looked like the geodesic domes invented by architect R. Buckminster Fuller, and they thus acquired the nickname "buckminsterfullerenes," soon shortened to "buckyballs."[12] Smalley and his colleagues would later garner the 1996 Nobel Prize in chemistry for this achievement. More recent work has led to the discovery of carbon nanotubules. These structures, similar to buckyballs, are sheets of carbon atoms, many thousands of atoms in length, rolled up into a cylinder. Depending on the way they are rolled these tiny tubules can behave like metals, semiconductors or a combination of both.[13] According to NASA researchers, nanotubules "are 100 times stronger than steel, but they weigh only one-sixth as much." While a long way from being mass-produced, they have the potential to generate lightweight, super-efficient computers and spacecraft.[14]

It is the great irony of the development of nanotechnology that the book which would help push it into mainstream culture would also do the most damage to its reputation as a credible science. *Engines of Creation*, published in 1986 by Eric Drexler, a researcher at the Massachusetts Institute of Technology, remains to date one of the most controversial works on the subject of nanotechnology.[15] Yet, while the godlike control over matter that Drexler envisioned was ridiculed by many academics, *Engines of Creation* and the numerous science

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(10) Richard P. Feynman, "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics," full text available at http://www.zyvex.com/nanotech/feynman.html.

(11) "Nanotech Executive Summary," *Technology Review*, 12 October 2001, http://www.technologyreview.com/articles/nanotech101.asp.

(12) *Ibid*.

(13) *Ibid*.

(14) Margaret Munroe, "Small Miracles," *National Post*, 21 January 2002.

(15) "Nanotech Executive Summary," http://www.technologyreview.com/articles/nanotech101.asp.

fiction works it inspired spawned a public interest in nanotechnology which continues to benefit researchers.[16] That interest was heightened in 1990, when researchers at IBM surprised the world by spelling out their company's three-letter name using xenon atoms on a nickel surface. It was the first time anyone had built something by deliberately manipulating individual atoms.

POTENTIAL BENEFITS OF NANOTECHNOLOGY

Nanotechnology has the potential to have enormous impacts on nearly all areas of human activities, including the automotive and aeronautics industries, electronics and communications, chemicals and materials production, pharmaceuticals, health care, life sciences, manufacturing, environmental protection, energy technologies, space exploration and national security. Some specific applications may include:

- nanoparticle-reinforced materials that are stronger yet lighter than existing ones;
- improvements in both data storage capacity and computer processing speeds by factors of thousands to millions;
- catalysts that increase the energy efficiency of chemical plants and improve the combustion efficiency (thus lowering pollution emissions) of motor vehicle engines;
- new nanostructured drugs;
- gene and drug delivery systems targeted to specific sites in the body;
- biocompatible replacements for body parts and fluids;
- material for bone and tissue regeneration;
- artificial photosynthesis for clean energy;
- safe storage of hydrogen for use as a clean fuel;
- nanostructured traps for removing pollutants from industrial effluents;
- lightweight space vehicles;

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(16) Stix, pp. 36-37.

- ultra-small and capable robotic systems;
- detectors and detoxifiers of chemical and biological agents.

Advances in research at the nanoscale have already allowed scientists to realize improvements in computer data storage, solar cells, rechargeable batteries, lasers and magnetic disk heads.[17] Scientists are adding to their nanotechnology "tool kit" innovations that include tweezers composed of carbon nanotubules that can pick up individual particles.[18] By borrowing the molecular motors that cells use to power their own functions, researchers are taking the first steps towards powering nanoscale devices.[19]

GOVERNMENT INVESTMENT IN NANOTECHNOLOGY

In January 2000, U.S. President Bill Clinton announced the creation of the National Nanotechnology Initiative (NNI), a multi-agency program designed to support research on nanoscience in a broad range of scientific disciplines. The bulk of the funding was directed to the National Science Foundation, the Department of Defense and the Department of Energy.[20] The FY (fiscal year) 2001 budget thus included $422 million for nanotechnology spending, which represented a 56% increase over the previous year.[21] The FY 2002 budget enacted by Congress included a further increase of 43%, dedicating $604 million to nanotechnology funding; this was in marked contrast to the majority of the budget proposals made by the Bush

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(17) Robert F. Service, "Atom-Scale Research Gets Real," *Science*, vol. 290, no. 5496, 24 November 2000, pp. 1524-1532.

(18) Chad A. Mirkin, "Tweezers for the Nanotool Kit," *Science*, vol. 286, no. 5447, 10 December 1999, pp. 2095-2096.

(19) This has been accomplished by manipulating ATPase, the most ubiquitous cellular motor in the world's life forms, which does everything from ferrying cargo to flexing muscles to copying DNA. Robert F. Service, "Borrowing from Biology to Power the Petite," *Science*, vol. 283, no. 5398, 1 January 1999, pp. 27-28.

(20) National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology, *National Nanotechnology Initiative: The Initiative and its Implementation Plan*, July 2000, p. 15, http://www.nsf.gov/home/crssprgm/nano/nni2.pdf.

(21) National Nanotechnology Initiative, *National Nanotechnology Investment in the FY 2002 Budget Request by the President*, 5 February 2002, http://www.nano.gov/2002budget.html.

administration regarding federal agencies that support research and development.[22] Around the world, governments are aggressively investing in nanotechnology; Japan, China, Israel, Australia, South Korea, Great Britain and Russia are putting nearly $1 billion into basic nanotechnology research and development annually.[23]

In August 2001, the governments of Canada and Alberta announced the creation of the National Institute for Nanotechnology, a new national research facility dedicated to nanotech research and development to be located at the University of Alberta. The federal government and the Alberta government each promised $60 million in funding over a five-year period. With this initiative, Canada is aiming to join the United States, Europe and Asia in the creation of nanotech research centres.[24]

AREAS OF CONCERN

The pace at which nanotechnology is developing has caused a number of researchers and governments to give serious thought to the potential consequences that this science may have for the world. Because nanotechnology's impact is expected to be so broad in scope, touching everything from medicine to manufacturing to the environment to security, there is little doubt that its broader implications for society will be profound.[25] The most difficult impacts to predict will be those that are unintended consequences of the application of nanotechnology.[26] Furthermore, the harmful applications of nanotechnology – unintended or otherwise – will require serious consideration. How are we to monitor and police the use of

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(22) Stix, p. 33.

(23) Jack Uldrich, "Why Nanotechnology Will Arrive Sooner Than Expected," *The Futurist*, vol. 16, March-April 2002, p. 19.

(24) Government of Canada, Government of Alberta, Press Release, 17 August 2001, "$120-million National Institute at University of Alberta will make Canada a world leader in nanotechnology," http://www.nrc.ca/corporate/english/media/news/nano01_e.pdf.

(25) Mihail C. Roco and William Sims Bainbridge, eds., *Societal Implications of Nanoscience and Nanotechnology*, National Science Foundation, March 2001, Arlington, Virginia, p. 1.

(26) *Ibid*, pp. 10-11.

technology such as nanoweapons, intelligence-gathering devices or artificial viruses to which humans have no immunity?[27]

Another issue to consider is the question of public acceptance. For instance, while the concept of tiny machines that can be injected into the body to repair damage at the cellular level may sound great, individuals may be reluctant to be a "nanomedicine guinea pig."[28] In this area, public education will be key to avoiding negative public reactions. Nanotechnology may also challenge us in more abstract ways, testing our concepts of ownership and liability. For example, if a robot can self-replicate, does ownership carry over from one generation of machines to the next?[29]

Nanotechnology is also likely to have serious impacts on existing industries and technologies, rendering some of them unprofitable or obsolete. Predicting what industries will be marginalized by the application of nanotechnology and determining how society should respond will be extremely important in the coming years. For example, the impact on the manufacturing industry will need careful consideration, as it is likely to move increasingly towards a workforce of a small number of highly skilled people, exacerbating an existing trend.[30] If nanosystems help us produce alternatives to fossil fuels, what will become of the oil and gas sectors which play such important roles in the world's economies? Moreover, while it is possible that nanotechnology may have a positive impact on developing nations, it is also possible that the gap between the rich and poor of the world will only be further increased since the difference between those who have access to nanotechnologies and those who do not is likely to be striking.[31] It is imperative that government and the public begin to think about the potential consequences of nanotechnology so that we can meet its challenges head-on and well prepared.

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(27) Richard H. Smith, "Social, Ethical, and Legal Implications of Nanotechnology," in Roco and Bainbridge, pp. 203-211.

(28) Michael Brooks, "Thanks But No Thanks," *New Scientist*, 6 October 2001, p. 33.

(29) Mark C. Suchman, "Envisioning Life on the Nano-Frontier," in Roco and Bainbridge, pp. 211-216.

(30) M. Meyer, "Socio-Economic Research on Nanoscale Science and Technology: A European Review and Illustration," in Roco and Bainbridge, pp. 217-241.

(31) Smith, p. 204.

TECHNICAL OBSTACLES

Despite the tremendous advances in nanotechnology over the years and the great expectations many researchers have for the field, there remain a number of significant obstacles to be overcome. Firstly, the problem of manufacturability continues to plague nanotechnology's development. While a large number of technologies have been proved theoretically feasible, many remain confined to the drawing board as practical feasibility eludes researchers. Furthermore, connecting the nano world to our macro world also presents a great challenge. While it may be possible to build nanoscale machines, linking them in such a way as to allow them to be used as part of larger macroscale structures is quite difficult.(32) Implantable nanotechnology is also complicated by the fact that our bodies are "best designed to repel or attack things the size of a cell," meaning that any structures that we wish to introduce must be designed to be unrecognizable.(33) Recent research has also focused on the concept of "self-assembly," where molecules are designed and constructed in such a way that they will automatically arrange themselves into a desired configuration. This occurs in nature all the time; DNA is often cited as the perfect example of a self-assembling device. Such a system could potentially lead to complex self-replicating structures.(34) However, some researchers have pointed out that self-replicating nanomachines could easily get out of hand, making uncountable copies of themselves leading to a "grey goo" that ravages the Earth.(35)

CONCLUSION

Nanotechnology has emerged as one of the most exciting and promising fields of scientific research, mimicking some of the most complex systems found in nature and manipulating matter at the level where its basic properties are determined. Expectations are

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(32) Service, "Atom-Scale Research Gets Real," pp. 1524-1532.

(33) Brooks, p. 33.

(34) "Nanotech Executive Summary," http://www.technologyreview.com/articles/nanotech101.asp.

(35) George M. Whitesides, "The Once and Future Nanomachine," *Scientific American*, vol. 32, September 2001, pp. 78-83.

high, and while the "nanofuture" may not be exactly as we envision, it will no doubt entail profound changes in all areas of human life.

Some have argued that the investments made by governments in nanotechnology R&D will serve to drive growth in new fields and industries in the same way that the United States' aggressive funding for the NASA space programs in the 1950s and 1960s helped promote the computer and electronics industries. Only time will tell if the impacts of nanotechnology will be as profound and revolutionary as many anticipate; however, the investments made in this area by governments around the world will be certain to raise the profile of the physical sciences in general.

APPENDIX
OTHER POTENTIAL APPLICATIONS OF NANOTECHNOLOGY

- Molecular-scale super computers the size of a grain of salt
- Super-flat display screens
- Faster and more powerful, yet smaller, laptops
- New generations of lasers using nanoscale semiconducting material
- Superconducting nanotubes at room temperature, far above the current –143ºC maximum temperature required
- Molecules designed to hunt down and destroy cancerous tumours
- Gene and drug delivery systems targeted to specific sites in the body
- Implantable devices that monitor hormone levels and then synthesize more as needed
- New methods for manipulating gene expression
- New processes and tools to manipulate matter at the atomic level
- Precision engineering based on new generations of microscopes and measuring techniques
- Self-repairing metals and wires
- Self-cleaning and self-sterilizing surfaces
- Super-hard and tough drill bits and cutting tools
- New applications for labs-on-a-chip, such as improved sensors
- New types of batteries
- Energy savings from using lighter materials and smaller circuits
- Safe and affordable space travel using unmanned systems that use nanotechnology to grow new parts from raw materials or by cannibalizing old machines
- Selective membranes for filtering contaminants from water
- Molecular food synthesis
- Increased opportunities for recycling
- Miniaturized surveillance systems
- Fabrics that can change colour for camouflage purposes
- Fabrics that can stiffen to form emergency splints for broken limbs
- Self-assembling consumer goods