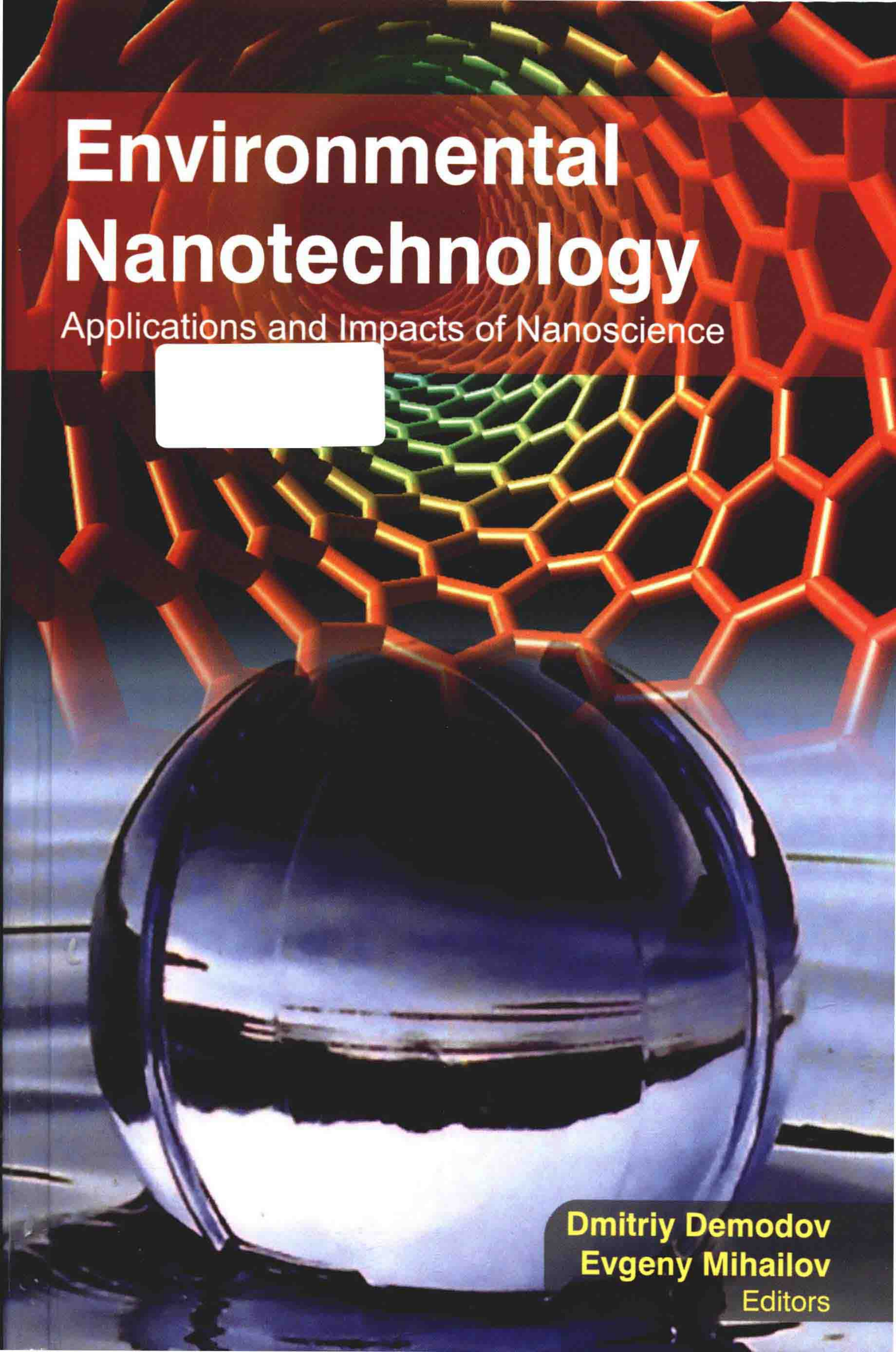
Environmental Nanotechnology

Applications and Impacts of Nanoscience



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Preface

Nanotechnology—a term encompassing nanoscale science, engineering, and technology—is focused on understanding, controlling, and exploiting the unique properties of matter that can emerge at scales of one to 100 nanometers. Nanotechnology is being used in several applications to improve the environment. This includes cleaning up existing pollution, improving manufacturing methods to reduce the generation of new pollution, and making alternative energy sources more cost effective. Nanotechnology offers tremendous opportunities to improve product performance, human health and welfare, and environmental protection. However, benefits arising from the opportunities created by emerging technologies must be balanced by understanding potential impacts and development of policies that protect public health and the environment. The next twenty years will likely see the creation of novel materials and compounds with the integration of nanotechnology and synthetic biology, nanotechnology and information technology, along with other innovative combinations and mergers. The development of increasingly active nano structures and true atom-by-atom construction of products is likely to occur during this time period as well. As we explore and develop technologies in the fields of energy production, storage and transmission, agriculture pest control and yield, medical therapy and imaging, food and water protection, and other improvements to our quality of life based upon these novel materials; exposure, toxicity and risk assessment data will be needed for successful deployment. In addition, social context is critical for determining whose quality of life is improved and whose may be impaired.

Some have described nanotechnology as a two-edged sword. On the one hand, some are concerned that nanoscale particles may enter and accumulate in vital organs, such as the lungs and brains, potentially causing harm or death to humans and animals, and that the diffusion of nanoscale particles in the environment might harm ecosystems. On the other hand, some believe that nanotechnology has the potential to deliver important environmental, health, and safety benefits such as reducing energy consumption, pollution, and greenhouse gas emissions; remediating environmental damage; curing, managing, or preventing diseases; and offering new safety-enhancing materials that are stronger, self-repairing, and able to adapt to provide protection. Stakeholders generally agree that concerns about potential detrimental effects of nanoscale materials and devices—both real and perceived—must be addressed to protect and improve human health, safety, and the environment; enable accurate and efficient risk assessment, risk management, and cost-benefit trade-offs; foster innovation and public confidence; and ensure that society can enjoy the widespread economic and societal benefits that nanotechnology may offer. Others express the view that concerns about nanotechnology. Environmental, health, and safety implications are often overgeneralized and overstated. Among the arguments they put forth are that nanoscale materials are frequently embedded in other materials as part of the manufacturing process; that some nanotechnology products, such as semiconductors, have nanoscale features but do not contain nanoscale particles; that nanotechnology materials may replace other materials that have significant and known risks; that some nanoscale particles tend to aggregate or agglomerate in the environment into larger particles that no longer have nanoscale dimensions; and that people are regularly exposed to nanoscale particles produced naturally and as incidental by-products of human activities.

Advocates and critics agree that potential environmental, health, and safety implications of nanotechnology must be addressed if the full economic and societal benefits of nanotechnology are to be achieved. There is also general agreement that the current body of knowledge of how nanoscale materials might affect humans and the environment is insufficient to assess, address, and manage the potential risks.

The book expounds the history, techniques, principles, devices and the future of environmental nanotechnology, with insights also being given on the scope, challenges, opportunities and the advent of this science in our daily life. This book is an authoritative, in-depth exploration of the environmental consequences of nano technology. It provides a detailed account of the potential environmental benefits of nano technology, describing environmental technologies as well as other applications that can foster sustainable use of resources.

—Editor

Contents

Chapter 1

Introduction

Nanotechnology

Nanotechnology (sometimes shortened to "nanotech") is the manipulation of matter on an atomic and molecular scale. The earliest, widespread description of nanotechnology referred to the particular technological goal of precisely manipulating atoms and molecules for fabrication of macroscale products, also now referred to as molecular nanotechnology. A more generalized description of nanotechnology was subsequently established by the National Nanotechnology Initiative, which defines nanotechnology as the manipulation of matter with at least one dimension sized from 1 to 100 nanometres. This definition reflects the fact that quantum mechanical effects are important at this quantum-realm scale, and so the definition shifted from a particular technological goal to a research category inclusive of all types of research and technologies that deal with the special properties of matter that occur below the given size threshold. It is therefore common to see the plural form "nanotechnologies" as well as "nanoscale technologies" to refer to the broad range of research and applications whose common trait is size. Because of the variety of potential applications (including industrial and military), governments have invested billions of dollars in nanotechnology research. Through its National Nanotechnology Initiative, the USA has invested 3.7 billion dollars. The European Union has invested 1.2 billion and Japan 750 million dollars.

Nanotechnology as defined by size is naturally very broad, including fields of science as diverse as surface science, organic chemistry, molecular biology, semiconductor physics, microfabrication, etc. The associated research and applications are equally diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale.

Scientists currently debate the future implications of nanotechnology. Nanotechnology may be able to create many new materials and devices with a vast range of applications, such as in medicine, electronics, biomaterials and energy production. On the other hand, nanotechnology raises many of the same issues as any new technology, including concerns about the toxicity and environmental impact of nanomaterials, and their potential effects on global economics, as well as speculation about various doomsday scenarios. These concerns have led to a debate among advocacy groups and governments on whether special regulation of nanotechnology is warranted.

History of Nanotechnology

The history of nanotechnology traces the development of the concepts and experimental work falling under the broad category of nanotechnology. Although nanotechnology is a relatively recent development in scientific research, the development of its central concepts happened over a longer period of time. The emergence of nanotechnology in the 1980s was caused by the convergence of experimental advances such as the invention of the scanning tunneling microscope in 1981 and the discovery of fullerenes in 1985, with the elucidation and popularization of a conceptual framework for the goals of nanotechnology beginning with the 1986 publication of the book *Engines of Creation*. The field was subject to growing public awareness and controversy in the early 2000s, with prominent debates about both its potential implications as well as the feasibility of the applications envisioned by advocates of molecular nanotechnology, and with governments moving to promote and fund research into nanotechnology. The early 2000s also saw the beginnings of commercial applications of nanotechnology, although these were limited to bulk applications of nanomaterials rather than the transformative applications envisioned by the field.

Conceptual Origins

Richard Feynman: The American physicist Richard Feynman lectured, "There's Plenty of Room at the Bottom," at an American Physical Society meeting at Caltech on December 29, 1959, which is often held to have provided inspiration for the field of nanotechnology.

Feynman had described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally smaller set, so on down to the needed scale. In the course of this, he noted, scaling issues would arise from the changing magnitude of various physical phenomena: gravity would become less important, surface tension and Van der Waals attraction would become more important.

After Feynman's death, scholars studying the historical development of nanotechnology have concluded that his actual role in catalyzing nanotechnology research was limited, based on recollections from many of the people active in the nascent field in the 1980s and 1990s. Chris Toumey, a cultural anthropologist at the University of South Carolina, found that the published versions of Feynman's talk had a negligible influence in the twenty years after it was first published, as measured by citations in the scientific literature, and not much more influence in the decade after the Scanning Tunneling Microscope was invented in 1981. Subsequently, interest in "Plenty of Room" in the scientific literature greatly increased in the early 1990s. This is probably because the term "nanotechnology" gained serious attention just before that time, following its use by K. Eric Drexler in his 1986 book, *Engines of Creation: The Coming Era of Nanotechnology*, which took the Feynman concept of a billion tiny factories and added the idea that they could make more copies of themselves via computer control instead of control by a human operator; and in a cover article headlined "Nanotechnology", published later that year in a mass-circulation science-oriented magazine, *OMNI*. Toumey's analysis also includes comments from distinguished scientists in nanotechnology who say that "Plenty of Room" did not influence their early work, and in fact most of them had not read it until a later date.

These and other developments hint that the retroactive rediscovery of Feynman's "Plenty of Room" gave nanotechnology a packaged history that provided an early date of December 1959, plus a connection to the charisma and genius of Richard Feynman. Feynman's stature as a Nobel laureate and as an iconic figure in 20th century science surely helped advocates of nanotechnology and provided a valuable intellectual link to the past.

Norio Taniguchi: The Japanese scientist Norio Taniguchi of the Tokyo University of Science used the term "nano-technology" in a 1974 conference, to describe semiconductor processes such as thin film deposition and ion beam milling exhibiting characteristic control on the order of a nanometre. His definition was, "'Nano-technology' mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or one molecule."

K. Eric Drexler: In the 1980s the idea of nanotechnology as a deterministic, rather than stochastic, handling of individual atoms and molecules was conceptually explored in depth by K. Eric Drexler, who promoted the technological significance of nano-scale phenomena and devices through speeches and two influential books.

In 1980, Drexler encountered Feynman's provocative 1959 talk "There's Plenty of Room at the Bottom" while preparing his initial scientific paper on the subject, "Molecular Engineering: An approach to the development of general capabilities for molecular manipulation," published in the *Proceedings of the National Academy of Sciences* in 1981. The term "nanotechnology" (which paralleled Taniguchi's "nano-technology") was independently applied by Drexler in his 1986 book *Engines of Creation: The Coming Era of Nanotechnology*, which proposed the idea of a nanoscale "assembler" which would be able to build a copy of itself and of other items of arbitrary complexity. He also first published the term "grey goo" to describe what might happen if a hypothetical self-replicating machine, capable of independent operation, were constructed and released. Drexler's vision of nanotechnology is often called "Molecular Nanotechnology" (MNT) or "molecular manufacturing."

His 1991 Ph.D. work at the MIT Media Lab was the first doctoral degree on the topic of molecular nanotechnology and (after some editing) his thesis, "Molecular Machinery and Manufacturing with Applications to Computation," was published as *Nanosystems: Molecular Machinery, Manufacturing, and Computation,* which received the Association of American Publishers award for Best Computer Science Book of 1992. Drexler founded the Foresight Institute in 1986 with the mission of "Preparing for nanotechnology." Drexler is no longer a member of the Foresight Institute.

Experimental Advances

Nanotechnology and nanoscience got a boost in the early 1980s with two major developments: the birth of cluster science and the invention of the scanning tunneling microscope (STM). These developments led to the discovery of fullerenes in 1985 and the structural assignment of carbon nanotubes a few years later

Invention of Scanning Probe Microscopy: The scanning tunneling microscope, an instrument for imaging surfaces at the atomic level, was developed in 1981 by Gerd Binnig and Heinrich Rohrer at

IBM Zurich Research Laboratory, for which they were awarded the Nobel Prize in Physics in 1986. Binnig, Calvin Quate and Christoph Gerber invented the first atomic force microscope in 1986. The first commercially available atomic force microscope was introduced in 1989.

IBM researcher Don Eigler was the first to manipulate atoms using a scanning tunneling microscope in 1989. He used 35 Xenon atoms to spell out the IBM logo. He shared the 2010 Kavli Prize in Nanoscience for this work.

Advances in Interface and Colloid Science: Interface and colloid science had existed for nearly a century before they became associated with nanotechnology. The first observations and size measurements of nanoparticles had been made during the first decade of the 20th century by Richard Adolf Zsigmondy, winner of the 1925 Nobel Prize in Chemistry, who made a detailed study of gold sols and other nanomaterials with sizes down to 10 nm using an ultramicroscope which was capable of visualizing particles much smaller than the light wavelength. Zsigmondy was also the first to use the term "nanometre" explicitly for characterizing particle size. In the 1920s, Irving Langmuir, winner of the 1932 Nobel Prize in Chemistry, and Katharine B. Blodgett introduced the concept of a monolayer, a layer of material one molecule thick. In the early 1950s, Derjaguin and Abrikosova conducted the first measurement of surface forces.

In 1974 the process of atomic layer deposition for depositing uniform thin films one atomic layer at a time was developed and patented by Tuomo Suntola and co-workers in Finland.

In another development, the synthesis and properties of semiconductor nanocrystals were studied. This led to a fast increasing number of semiconductor nanoparticles of quantum dots.

Discovery of Fullerenes: Fullerenes were discovered in 1985 by Harry Kroto, Richard Smalley, and Robert Curl, who together won the 1996 Nobel Prize in Chemistry. Smalley's research in physical chemistry investigated formation of inorganic and semiconductor clusters using pulsed molecular beams and time of flight mass spectrometry. As a consequence of this expertise, Curl introduced him to Kroto in order to investigate a question about the constituents of astronomical dust. These are carbon rich grains expelled by old stars such as R Corona Borealis. The result of this collaboration was the discovery of C_{60} and the fullerenes as the third allotropic form of carbon. Subsequent discoveries included the endohedral fullerenes, and the larger family of fullerenes the following year.

The discovery of carbon nanotubes is largely attributed to Sumio Iijima of NEC in 1991, although carbon nanotubes have been produced and observed under a variety of conditions prior to 1991. Iijima's discovery of multi-walled carbon nanotubes in the insoluble material of arc-burned graphite rods in 1991 and Mintmire, Dunlap, and White's independent prediction that if single-walled carbon nanotubes could be made, then they would exhibit remarkable conducting properties helped create the initial buzz that is now associated with carbon nanotubes. Nanotube research accelerated greatly following the independent discoveries by Bethune at IBM and Iijima at NEC of *single-walled* carbon nanotubes and methods to specifically produce them by adding transition-metal catalysts to the carbon in an arc discharge.

In the early 1990s Huffman and Kraetschmer, of the University of Arizona, discovered how to synthesize and purify large quantities of fullerenes. This opened the door to their characterization and functionalization by hundreds of investigators in government and industrial laboratories. Shortly after, rubidium doped C_{60} was found to be a mid temperature (Tc = 32 K) superconductor. At a meeting of the Materials Research Society in 1992, Dr. T. Ebbesen (NEC) described to a spellbound audience his discovery and characterization of carbon nanotubes. This event sent those in attendance and others downwind of his presentation into their laboratories to reproduce and push those discoveries forward. Using the same or similar tools as those used by Huffman and Kratschmere, hundreds of researchers further developed the field of nanotube-based nanotechnology.

Government Support

National Nanotechnology Initiative: The National Nanotechnology Initiative is a United States federal nanotechnology research and development program. "The NNI serves as the central point of communication, cooperation, and collaboration for all Federal agencies engaged in nanotechnology research, bringing together the expertise needed to advance this broad and complex field." Its goals are to advance a world-class nanotechnology research and development (R&D) program, foster the transfer of new technologies into products for commercial and public benefit, develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology, and support responsible development of nanotechnology. The initiative was spearheaded by Mihail Roco, who formally proposed the National Nanotechnology Initiative to the Office of Science and Technology Policy during the Clinton administration in 1999, and was a key architect in its development. He is currently the Senior Advisor for Nanotechnology at the National Science Foundation, as well as the founding chair of the National Science and Technology Council subcommittee on Nanoscale Science, Engineering and Technology.

President Bill Clinton advocated nanotechnology development. In a 21 January 2000 speech at the California Institute of Technology, Clinton said, "Some of our research goals may take twenty or more years to achieve, but that is precisely why there is an important role for the federal government." Feynman's stature and concept of atomically precise fabrication played a role in securing funding for nanotechnology research, as mentioned in President Clinton's speech:

My budget supports a major new National Nanotechnology Initiative, worth $500 million. Caltech is no stranger to the idea of nanotechnology - the ability to manipulate matter at the atomic and molecular level. Over 40 years ago, Caltech's own Richard Feynman asked, "What would happen if we could arrange the atoms one by one the way we want them?"

President George W. Bush further increased funding for nanotechnology. On December 3, 2003 Bush signed into law the 21st Century Nanotechnology Research and Development Act, which authorizes expenditures for five of the participating agencies totaling US$3.63 billion over four years. The NNI budget supplement for Fiscal Year 2009 provides $1.5 billion to the NNI, reflecting steady growth in the nanotechnology investment.

Growing Public Awareness and Controversy

"Why the Future doesn't Need Us": "Why the future doesn't need us" is an article written by Bill Joy, then Chief Scientist at Sun Microsystems, in the April 2000 issue of *Wired* magazine. In the article, he argues that "Our most powerful 21st-century technologies — robotics, genetic engineering, and nanotech — are threatening to make humans an endangered species." Joy argues that developing technologies provide a much greater danger to humanity than any technology before it has ever presented. In particular, he focuses on genetics, nanotechnology and robotics. He argues that 20th century technologies of destruction, such as the nuclear bomb, were limited to large governments, due to the complexity and cost of such devices, as well as the difficulty in acquiring the required materials. He also voices concern about increasing computer power. His worry is that computers will eventually become more intelligent than we are, leading to such dystopian scenarios as robot rebellion. He notably quotes the Unabomber on this topic. After the publication of the article, Bill Joy suggested assessing technologies to gauge their implicit dangers, as well as having scientists refuse to work on technologies that have the potential to cause harm.

In the AAAS Science and Technology Policy Yearbook 2001 article titled *A Response to Bill Joy and the Doom-and-Gloom Technofuturists*, Bill Joy was criticized for having technological tunnel vision on his prediction, by failing to consider social factors. In Ray Kurzweil's *The Singularity Is Near*, he questioned the regulation of potentially dangerous technology, asking "Should we tell the millions of people afflicted with cancer and other devastating conditions that we are canceling the development of all bioengineered treatments because there is a risk that these same technologies may someday be used for malevolent purposes?".

Prey: *Prey* is a 2002 novel by Michael Crichton which features an artificial swarm of nanorobots which develop intelligence and threaten their human inventors. The novel generated concern within the nanotechnology community that the novel could negatively affect public perception of nanotechnology by creating fear of a similar scenario in real life.

Drexler–Smalley Debate: Richard Smalley, best known for co-discovering the soccer ball-shaped "buckyball" molecule and a leading advocate of nanotechnology and its many applications, was an outspoken critic of the idea of molecular assemblers, as advocated by Eric Drexler. In 2001 he introduced scientific objections to them attacking the notion of universal assemblers in a 2001 *Scientific American* article, leading to a rebuttal later that year from Drexler and colleagues, and eventually to an exchange of open letters in 2003.

Smalley criticized Drexler's work on nanotechnology as naive, arguing that chemistry is extremely complicated, reactions are hard to control, and that a universal assembler is science fiction. Smalley believed that such assemblers were not physically possible and introduced scientific objections to them. His two principal technical objections, which he had termed the "fat fingers problem" and the "sticky fingers problem", argued against the feasibility of molecular assemblers being able to precisely select and place individual atoms. He also believed that Drexler's speculations about apocalyptic dangers of molecular assemblers threaten the public support for development of nanotechnology.