Advances in Molecular Nanotechnology from Premodern to Modern Era

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***Abstract*—Beginning as early at the 1930s, scientists were able to see at the nanoscale using instruments such as the scanning electron microscope, the transmission electron microscope, and the field ion microscope. The most recent and notable developments in microscopy are the scanning tunneling microscope and the atomic force microscope. Manufacturing at the nanoscale is known as nanomanufacturing. Nanomanufacturing involves scaled-up, reliable, and cost-effective manufacturing of nanoscale materials, structures, devices, and systems. It also includes research, development, and integration of top-down processes and increasingly complex bottom-up or self-assembly processes. Structures and properties of materials can be improved through these nanomanufacturing processes. Early examples of nanostructure materials were based on craftsmen's empirical understanding and manipulation of materials. Use of high heat was one common step in their processes to produce these materials with novel properties. Nanotechnology in the modern era is based on increasingly sophisticated scientific understanding and instrumentation, as well as experimentation.**

***Index Terms*—nanomanufacturing, nanomaterials, nanoscale, nanotechnology**

I. Introduction

Nanotechnology is the science of modifying objects at the atomic or molecular level. Professionals in this field measure items in terms of nanometers, which is equal to one-billionth of a meter or 10^{-9} of a meter. Using nanotechnology, scientists build objects molecule-by-molecule, resulting in near-perfect products that far surpass any existing objects in terms of performance, effectiveness and longevity. This futuristic field of science actually dates back to 1959, though most of the major advances in nanotechnology have come in the past two decades. This technology also helps manufacturers make our favorite electronics smaller more portable. But the most exciting applications of this technology have come in breakthroughs made in recent years, as scientists have developed ways to apply nanotechnology to fields like medicine, robotics and the environment.

Clean Energy Sources: New breakthroughs in molecular nanotechnology may be the solution to the world's dependency on fossil fuels. Using nanotechnology to modify materials at the atomic level has allowed scientists to produce solar cells that are five times more effective than traditional silicon-based units. While solar panels currently in use capture only about 6 percent of solar energy, new technologies allow panels to capture up to 30 percent of solar energy, including invisible infrared rays. Installing these new solar cells across just 0.1 percent of the earth's surface would supply enough energy to eliminate the need for oil. Even better, these small flexible solar cells could be woven into the clothes we wear to charge a cell phone or computer on the go. Solar cells in cars could even be used to charge our car battery, making gas stations obsolete [1]. Traditional fuel cells resemble a battery pack, but contain an internal membrane that allows only hydrogen to pass through to supply power. Using principles of nanotechnology, manufacturers can make this membrane even more efficient, resulting in lightweight, high-powered fuel cells [2].

Nanorobots: The concept of nanorobotics reads like something straight out of science fiction where microscopic assemblers work in mini, self-contained factories. These nanofactories would fit right on a standard tabletop and measure not much bigger than a breadbox. Carbon-based "robots" within the factory could not only produce consumer goods like hardware and electronics, but also self-replicate to create new robots to join the workforce. Some of these newly created assemblers would also be used in healthcare, and could be released into the human body to capture cell-level images, repair wounds or even fix damaged DNA. Robots within the factory would build products from the atomic level up, creating an essentially perfect object. By eliminating flaws and creating high-quality materials without the need for human labor, nanorobots would produce objects quicker and at a lower cost than traditional manufacturing processes [3]. While nanorobots are likely several decades away at the earliest, recent advances in nanotechnology have helped pave the way for this type of technology. In 2006, the Foresight Institute awarded its annual innovation award to researchers who developed methods that will allow nanorobots to self-replicate using DNA [4]. In 2010, IBM introduced a micro-milling process that's capable of etching 1,000 3-D maps of the world on a single grain of salt [5]. New materials like graphene, which measures just one atom thick also promise to advance the development of nanorobotics [6].

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Accessible Medical Testing: In many developing countries, a lack of adequate medical facilities makes testing and treating diseases extremely difficult. Even treatable ailments like malaria and tuberculosis continue to claim more than 3 million lives a year worldwide due to lack of resources [7]. The U.S.-based Micronics Corporation has developed the DxBox, a disease testing kit no larger than a credit card. Using dried reagents and nano-plumbing systems built into the face of the card, doctors can perform basic blood tests without the need for refrigeration or any special supplies. The small size and cutting-edge technology used to produce these test kits makes them more effective and portable than any other type of malaria test, allowing doctors to test people in even the most remote or underdeveloped regions. The DxBox testing system can be used, not only for malaria and tuberculosis, but also to test nearly a half-dozen other diseases, most of which are easily treated. By providing a quick and accurate diagnosis, these test kits allow doctors to determine proper treatment, which can help save lives [8].

Effective Environmental Cleanup: A staggering 600 million people worldwide suffer ill health effects from polluted or insufficient water supplies, and this number could easily top 2 billion within the next two decades [9]. Fortunately, a number of advances in nanotechnology may help ease the effects of water shortages by removing pollutants, or by helping people use water more effectively. One of the biggest breakthroughs in terms of water conservation comes in the form of nanomagnets. These microscopic magnetic particles can capture arsenic in water, leaving it clean enough to drink. This technology removes as much as 99 percent of arsenic from water, which stands to benefit as many as 65 million people worldwide [10]. According to the U.S. Environmental Protection Agency, special iron-based nano filters can serve as effective and low-cost alternatives to traditional carbon-based water filters. These tiny iron particles form a membrane barrier to quickly clean groundwater supplies much faster than traditional pumping techniques. Using microscopic iron particles to treat dirty water can remove large volumes of chlorine, mercury or even radon [11]. Nanotechnology may even allow manufacturers to reduce water and air pollution associated with fossil fuel extraction. The process involves the use of zeolites, or tiny rock particles filled with an infinite number of microscopic holes. The zeolites serve as filters for oil sands and other fossil fuel sources, and allow workers to capture the oil without releasing harmful levels of carbon dioxide into the air. By cutting CO_2 emissions, zeolites also keep potential pollutants from contaminating groundwater and nearby water bodies [12]. Nanotubes can be wide enough to allow water to pass through, but narrow enough to prevent even small particles of pollutant from getting through.

A Better Cancer Treatment: Modern chemotherapy provides one of the most effective methods for eliminating cancerous cells and preventing them from spreading. Unfortunately, the same powerful chemo drugs that kill cancer can also damage healthy cells, leaving patients vulnerable to other illnesses, pain and nausea. Recent advances in molecular nanotechnology can control the spread of chemotherapy drugs, and direct them only to where they're needed. In 2006, scientists at MIT and Harvard used nanotechnology to destroy prostate cancer cells without damaging healthy tissues nearby [13]. In a similar 2010 study, researchers at Johns Hopkins University were able to treat breast cancer patients using nanoparticles rather than traditional chemo methods [14]. Each of these researchers relied on ultrasound bubbles, which consist of microscopic particles equipped with cancer-fighting drugs. At room temperature, the particles remain stable, but when exposed to body temperature, they join together to form larger particles. Using ultrasound waves, scientists can send signals to the "bubbles" to instruct them when and where to release the medication [15]. Nanoparticles may also give medical professionals a glance into individual cells within the body. Using fluorescent semiconductor crystals, researchers have been able to spot pre-cancerous cells in the colon, leading to early treatment and prevention [16].

Nanomaterials in Cosmetics: The two main uses for nanoparticles in cosmetic products are UV filtering and delivery of active ingredients. Titanium dioxide and zinc oxide are both used extensively in sunscreens to prevent UV damage to the skin - the nanoformulations of these materials have been shown repeatedly to give much better performance than larger particles, reflecting visible light and absorbing UV with very high efficiency. A number of modifications to the standard ZnO or TiO_2 UV protection system have been reported. Oxonica have developed Optisol, a UV absorption system which contains TiO_2 and 1% manganese [17]. Dispersing carnauba wax nanoparticles with TiO_2 nanoparticles was found to increase the sun protection factor (SPF) [18]. Nanphase Technologies, who supply nanoparticles to companies including BASF, produce controllable polymeric nanocrystals of ZnO with a size less than 35 nm for personal care applications [19]. Other nanoparticles have been developed for UV protection. Rohm and Haas produce hollow styrene acrylate copolymer nanoparticles, ~300nm in size, that are reported to increase SPF by about 70 % [20].

II. Methodology

Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale. Matter such as gases, liquids, and solids can exhibit unusual physical, chemical, and biological properties at the nanoscale, differing in important ways from the properties of bulk materials and single atoms or molecules. Some nanostructured materials are stronger or have different magnetic properties compared to other forms or sizes or the same material. Others are better at conducting heat or electricity. They may become more chemically reactive or reflect light better or change color as their size or structure is altered.

Exploring the World through Microscopes: Beginning as early at the 1930s, scientists were able to see at the nanoscale using instruments such as the scanning electron microscope, the transmission electron microscope, and the field ion microscope. The most recent and notable developments in microscopy are the scanning tunneling microscope and the atomic force microscope. The electron microscope uses a particle beam of electrons to illuminate a specimen and create a highly magnified image. Electron microscopes yield much greater resolution than the older light microscopes; they can obtain magnifications of up to 1 million times, while the best light microscopes can magnify an image only about 1,500 times. The scanning tunneling microscope (STM) is among a number of instruments that allows scientists to view and manipulate nanoscale particles, atoms, and small molecules. Its development earned its inventors, Gerd Binig and Heinrich Rohrer, the Nobel Prize in Physics in 1986. Atomic force microscopes (AFMs) gather information by "feeling" the surface with a mechanical probe. Gerd Binig, along with Calvin Quate and Christoph Gerber, developed the first AFM in 1986. These microscopes make use of tiny but exact movements to enable precise mechanical scanning.

Manufacturing at the Nanoscale: Manufacturing at the nanoscale is known as nanomanufacturing. Nanomanufacturing involves scaled-up, reliable, and cost effective manufacturing of nanoscale materials, structures, devices and systems. It also includes research, development, and integration of top-down processes and increasingly complex bottom-up or self-assembly processes. In more simple terms, nanomanufacturing leads to the production of improved materials and new products. In the "top-down" approach, nano-objects are constructed from larger entities without atomic-level control [21]. In the "bottom-up" approach, materials and devices are built from molecular components which assemble themselves chemically by principles of molecular recognition.

There are a growing number of new processes that enable nanomanufacturing. Among these are: Chemical vapor deposition is a process in which chemicals react to produce very pure, high-performance films, Molecular beam epitaxy is one method for depositing highly controlled thin films, Atomic layer epitaxy is a process for depositing one-atom-thick layers on a surface, Dip pen lithography is a process in which the tip of an atomic force microscope is "dipped" into a chemical fluid and then used to "write" on a surface, like an old fashioned ink pen onto paper, Nanoimprint lithography is a process for creating nanoscale features by "stamping" or "printing" them onto a surface, Roll-to-roll processing is a high-volume process to produce nanoscale devices on a roll of ultrathin plastic or metal.

Structures and properties of materials can be improved through these nanomanufacturing processes. Such nanomaterials can be stronger, lighter, more durable, water-repellent, anti-reflective, self-cleaning, ultraviolet or infrared resistant, antifog, antimicrobial, scratch resistant, or electrically conductive, among other traits. Taking advantage of these properties, today's nanotechnology enabled products range from baseball bats and tennis rackets to catalysts for refining crude oil and ultrasensitive detection and identification of biological and chemical toxins. Nanoparticles and other nanostructured materials have unique properties which cannot be achieved when working with the bulk form of the material. Applications for these special properties have been suggested in many industries the cosmetics industry is one of those most eager to make the most of the opportunities presented by nanotechnology. Nanomaterials have been used to try and improve the performance of a wide range of products.

III. Observation

Nanotechnology in the Premodern Era: Early examples of nanostructure materials were based on craftsmen's empirical understanding and manipulation of materials. Use of high heat was one common step in their processes to produce these materials with novel properties.

4^{th} Century: The Lycurgus Cup (Rome) is an example of dichroic glass; colloidal gold and silver in the glass allow it to look opaque green when lit from outside as shown in Fig. 1(A) but translucent red when light shines through the inside as shown in Fig. 1(B).

6^{th}-15^{th} Centuries: Vibrant stained glass windows in European cathedrals as shown in Fig. 1(C) owed their rich colors to nanoparticles of gold chloride and other metal oxides and chlorides; gold nanoparticles also acted as photocatalytic air purifiers.

9^{th}-17^{th} Centuries: Glowing, glittering "luster" ceramic glazes used in the Islamic world, and later in Europe, contained silver or copper or other metallic nanoparticles Fig. 1(D).

(A) (B) (C) (D)

Figure 1. Lycurgus cup at the British museum (A) & (B); south rose window of notre dame cathedral ca 1250 (C); polychrome lustreware bowl 9th C Iraq British museum (D)

(A) (B)

Figure 2. Damascus saber (A); high-resolution transmission electron microscopy image of carbon nanotubes in a genuine damascus sabre after dissolution in hydrochloric acid, showing remnants of cementite nanowires encapsulated by carbon nanotubes (B)

13th-18th Centurties: "Damascus" saber blades contained carbon nanotubes and cementite nanowires-an ultrahigh carbon steel formulation that gave them strength, resilience, the ability to hold a keen edge, and a visible moiré pattern in the steel that give the blades their name Fig. 2(A) and Fig. 2(B).

Nanotechnology in the modern era: These are based on increasingly sophisticated scientific understanding and instrumentation, as well as experimentation.

1857: Michael Faraday discovered colloidal "ruby" gold, demonstrating that nanostructured gold under certain lighting conditions produces different-colored solutions.

1936: Erwin Müller, working at Siemens Research Laboratory, invented the field emission microscope, allowing near-atomic-resolution images of materials.

1947: John Bardeen, William Shockley, and Walter Brattain at Bell Labs discovered the semiconductor transistor and greatly expanded scientific knowledge of semiconductor interfaces, laying the foundation for electronic devices and the Information Age.

1950: Victor La Mer and Robert Dinegar developed the theory and a process for growing monodisperse colloidal materials. Controlled ability to fabricate colloids enables myriad industrial uses such as specialized papers, paints, and thin films, even dialysis treatments.

1951: Erwin Müller pioneered the field ion microscope, a means to image the arrangement of atoms at the surface of a sharp metal tip; he first imaged tungsten atoms.

1956: Arthur von Hippel at MIT introduced many concepts of and coined the term "molecular engineering" as applied to dielectrics, ferroelectrics and piezoelectrics.

1958: Jack Kilby of Texas Instruments originated the concept of, designed, and built the first integrated circuit, for which he received the Nobel Prize in 2000.

1959: Richard Feynman of the California Institute of Technology gave what is considered to be the first lecture on technology and engineering at the atomic scale, "There's Plenty of Room at the Bottom" at an American Physical Society meeting at Caltech.

1965: Intel co-founder Gordon Moore described in Electronics magazine several trends he foresaw in the field of electronics. One trend now known as "Moore's Law," described the density of transistors on an integrated chip (IC) doubling every 12 months (later amended to every 2 years). Moore also saw chip sizes and costs shrinking with their growing functionality—with a transformational effect on the ways people live and work. That the basic trend Moore envisioned has continued for 50 years is to a large extent due to the semiconductor industry's increasing reliance on nanotechnology as ICs and transistors have approached atomic dimensions.

1974: Tokyo Science University Professor Norio Taniguchi coined the term nanotechnology to describe precision machining of materials to within atomic-scale dimensional tolerances.

1981: Gerd Binnig and Heinrich Rohrer at IBM's Zurich lab invented the scanning tunneling microscope, allowing scientists to "see" (create direct spatial images of) individual atoms for the first time. The invention of the scanning tunneling microscope in 1981 provided unprecedented visualization of individual atoms and bonds, and was successfully used to manipulate individual atoms in 1989 [22, 23]. Binnig, Quate and Gerber also invented the analogous atomic force microscope that same year.

Russia's Alexei Ekimov discovered nanocrystalline, semiconducting quantum dots in a glass matrix and conducted pioneering studies of their electronic and optical properties.

1985: Rice University researchers Harold Kroto, Sean O'Brien, Robert Curl, and Richard Smalley discovered the Buckminsterfullerene (C60), more commonly known as the buckyball as shown in Fig. 3(A), which is a molecule resembling a soccerball in shape and composed entirely of carbon, as are graphite and diamond [24, 25].

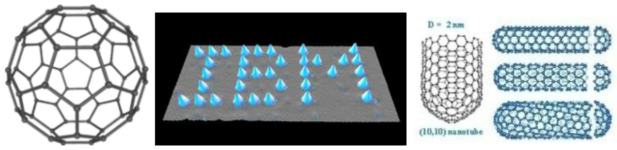
Bell Labs's Louis Brus discovered colloidal semiconductor nanocrystals (quantum dots).

1986: Gerd Binnig, Calvin Quate, and Christoph Gerber invented the atomic force microscope, which has the capability to view, measure, and manipulate materials down to fractions of a nanometer in size, including measurement of various forces intrinsic to nanomaterials.

1989: Don Eigler and Erhard Schweizer at IBM's Almaden Research Center manipulated 35 individual xenon atoms to spell out the IBM logo Fig. 3(B). This demonstration of the ability to precisely manipulate atoms ushered in the applied use of nanotechnology.

1990: Early nanotechnology companies began to operate, e.g. Nanophase Technologies in 1989, Helix Energy Solutions Group in 1990, Zyvex in 1997, Nano-Tex in 1998.

1991: Sumio Iijima of NEC is credited with discovering the carbon nanotube (CNT), although there were early observations of tubular carbon structures by others as well. CNTs Fig. 3(C), like buckyballs, are entirely composed of carbon, but in a tubular shape. They exhibit extraordinary properties in terms of strength, electrical and thermal conductivity, among others. The properties of CNTs are being explored for applications in electronics, photonics, multifunctional fabrics, biology (e.g. as a scaffold to grow bone cells) and communications.



(A) (B) (C)

Figure 3. Buckminsterfullerene C_{60} - the buckyball (A); IBM logo written with 35 xenon atoms on a copper substrate (B); Carbon nanotubes (C)

1992: C.T. Kresge and colleagues at Mobil Oil discovered the nanostructured catalytic materials MCM-41 and MCM-48, now used heavily in refining crude oil as well as for drug delivery, water treatment, and other varied applications.

1993: Moungi Bawendi of MIT invented a method for controlled synthesis of nanocrystals (quantum dots), paving the way for applications ranging from computing to biology to high-efficiency photovoltaics and lighting. Within the next several years, work by other researchers such as Louis Brus and Chris Murray also contributed methods for synthesizing quantum dots.

1998: The Interagency Working Group on Nanotechnology (IWGN) was formed under the National Science and Technology Council to investigate the state of the art in nanoscale science and technology and to forecast possible future developments. The IWGN's study and report, NanotechnologyResearch Directions-Vision for the Next Decade (1999) defined the vision for and led directly to formation of the U.S. National Nanotechnology Initiative in 2000.

1999: Cornell University researchers Wilson Ho and Hyojune Lee probed secrets of chemical bonding as shown in Fig. 4 by assembling a molecule [iron carbonyl Fe(CO)2] from constituent components [iron (Fe) and carbon monoxide (CO)] with a scanning tunneling microscope[26].

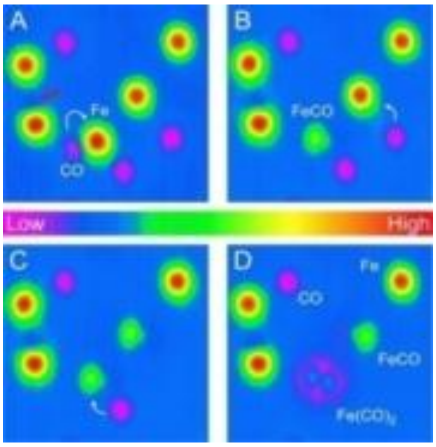


Figure 4. The progression of steps of using a scanning tunneling microscope tip to "assemble" an iron carbonyl molecule, beginning with Fe (iron) and CO (carbon monoxide) molecules (A), joining them to produce FeCO (B), then adding a second CO molecule (C), to achieve the Fe(CO)2 molecule (D)

Chad Mirkin at Northwestern University invented dip-pen nanolithography (DPN), leading to manufacturable, reproducible "writing" of electronic circuits as well as patterning of biomaterials for cell biology research, nanoencryption, and other applications Fig. 5.

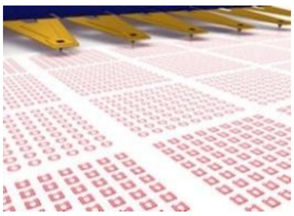


Figure 5. Use of DPN to deposit biomaterials

Early 2000: Consumer products making use of nanotechnology began appearing in the marketplace, including lightweight nanotechnology-enabled automobile bumpers that resist denting and scratching, golf balls that fly straighter, tennis rackets that are stiffer (therefore, the ball rebounds faster), baseball bats with better flex and "kick," nano-silver antibacterial socks, clear sunscreens, wrinkle- and stain-resistant clothing, deep-penetrating therapeutic cosmetics, scratch-resistant glass coatings, faster-recharging batteries for cordless electric tools, and improved displays for televisions, cell phones, and digital cameras.

2000: President Clinton launched the National Nanotechnology Initiative (NNI) to coordinate Federal R&D efforts and promote U.S. competitiveness in nanotechnology. Congress funded the NNI for the first time in FY2001. The NSET Subcommittee of the NSTC was designated as the interagency group responsible for coordinating the NNI.

2003: Congress enacted the 21st Century Nanotechnology Research and Development Act (P.L. 108-153). The act provided a statutory foundation for the NNI, established programs, assigned agency responsibilities, authorized funding levels, and promoted research to address key issues.

Naomi Halas, Jennifer West, Rebekah Drezek, and Renata Pasqualin at Rice University developed gold nanoshells, as shown in Fig. 6 which when "tuned" in size to absorb near-infrared light, serve as a platform for the integrated discovery, diagnosis, and treatment of breast cancer without invasive biopsies, surgery, or systemically destructive radiation or chemotherapy.

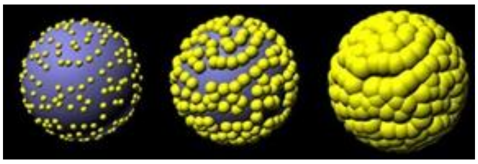


Figure 6. Computer simulation of growth of gold nanoshell with silica core and over-layer of gold

2004: The European Commission adopted the Communication "Towards a European Strategy for Nanotechnology," COM (2004) 338, which proposed institutionalizing European nanoscience and nanotechnology R&D efforts within an integrated and responsible strategy, and which spurred European action plans and ongoing funding for nanotechnology R&D.

Britain's Royal Society and the Royal Academy of Engineering published Nanoscience and Nanotechnologies: Opportunities and Uncertainties advocating the need to address potential health, environmental, social, ethical, and regulatory issues associated with nanotechnology.

SUNY Albany launched the first college-level education program in nanotechnology in the United States, the College of Nanoscale Science and Engineering.

2005: ErikWinfree and Paul Rothemund from the California Institute of Technology developed theories for DNA-based computation and "algorithmic self-assembly" in which computations are embedded in the process of nanocrystal growth.

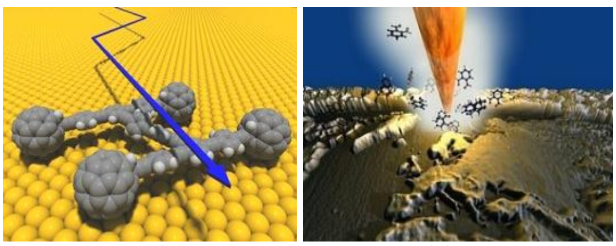
2006: James Tour and colleagues at Rice University built a nanoscale car made of oligo (phenylene ethynylene) with alkynyl axles and four spherical C60 fullerene (buckyball) wheels Fig. 7(A). In response to increases in temperature, the nanocar moved about on a gold surface as a result of the buckyball wheels turning, as in a conventional car. At temperatures above 300℃ it moved around too fast for the chemists to keep track of it!

2007: Angela Belcher and colleagues at MIT built a lithium-ion battery with a common type of virus that is nonharmful to humans, using a low-cost and environmentally benign process. The batteries have the same energy capacity and power performance as state-of-the-art rechargeable batteries being considered to power plug-in hybrid cars, and they could also be used to power personal electronic devices.

2008: The first official NN1 Strategy for Nanotechnology-Related Environmental, Health, and Safety (EHS) Research was published, based on a two-year process of NNI-sponsored investigations and public dialogs. This strategy document was updated in 2011, following a series of workshops and public review.

2009: Nadrian Seeman and colleagues at New York University created several DNA-like robotic nanoscale assembly devices. One is a process for creating 3D DNA structures using synthetic sequences of DNA crystals that can be programmed to self-assemble using “sticky ends” and placement in a set order and orientation. Nanoelectronics could benefit: the flexibility and density that 3D nanoscale components allow could enable assembly of parts that are smaller, more complex, and more closely spaced. Another Seeman creation (with colleagues at China’s Nanjing University) is a “DNA assembly line”.

2010: IBM used a silicon tip measuring only a few nanometers at its apex (similar to the tips used in atomic force microscopes) to chisel away material from a substrate to create a complete nanoscale 3D relief map of the world one-one-thousandth the size of a grain of salt in 2 minutes and 23 seconds Fig. 7(B). This activity demonstrated a powerful patterning methodology for generating nanoscale patterns and structures as small as 15 nanometers at greatly reduced cost and complexity, opening up new prospects for fields such as electronics, optoelectronics, and medicine.



(A) (B)

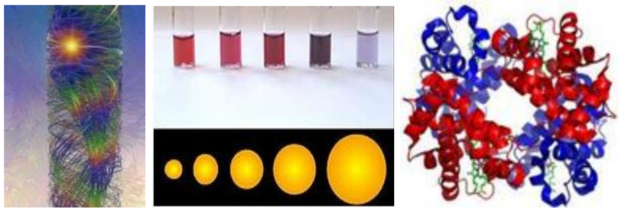
Figure 7. Nanocar with turning buckyball wheels (A); A rendered image of a nanoscale silicon tip chiseling out the smallest relief map of the world from a substrate of organic molecular glass. Shown middle foreground is the Mediterranean Sea and Europe (B)

2011: The NSET Subcommittee updated both the NNI Strategic Plan and the NNI Environmental, Health, and Safety Research Strategy, drawing on extensive input from public workshops and online dialog with stakeholders from Government, academia, NGOs, and the public, and others.

2012: The NNI launched two more Nanotechnology Signature Initiatives (NSIs) Nanosensors and the Nanotechnology Knowledge Infrastructure (NKI) bringing the total to five NSIs.

2013: The NNI starts the next round of Strategic Planning, starting with the Stakeholder Workshop.

Stanford researchers develop the first carbon nanotube computer.



(A) (B) (C)

Figure 8. Computer simulation of electron motions within a nanowire that has a diameter in the nanoscale range (A); Nanoscale gold (B); Computer simulation of hemoglobin, a naturally occuring nanoscale protein that is found in blood (C)

IV. Result and Discussion

Scale at which quantum effects dominate properties of materials: When particle sizes of solid matter in the visible scale are compared to what can be seen in a regular optical microscope, there is little difference in the properties of the particles. But when particles are created with dimensions of about 1-100 nanometers (where the particles can be “seen” only with powerful specialized microscopes), the materials’ properties change significantly from those at larger scales Fig. 8(A). This is the size scale where so-called quantum effects rule the behavior and properties of particles. Properties of materials are size-dependent in this scale range. Thus, when particle size is made to be nanoscale, properties such as melting point, fluorescence, electrical conductivity, magnetic permeability, and chemical reactivity change as a function of the size of the particle.

Nanoscale gold illustrates the unique properties that occur at the nanoscale. Nanoscale gold particles are not the yellow color with which we are familiar; nanoscale gold can appear red or purple Fig. 8(B). At the nanoscale, the motion of the gold’s electrons is confined. Because this movement is restricted, gold nanoparticles react differently with light compared to larger-scale gold particles. Their size and optical properties can be put to practical use: nanoscale gold particles selectively accumulate in tumors, where they can enable both precise imaging and targeted laser destruction of the tumor by means that avoid harming healthy cells.

A fascinating and powerful result of the quantum effects of the nanoscale is the concept of “tunability” of properties. That is, by changing the size of the particle, a scientist can literally fine-tune a material property of interest (e.g., changing fluorescence color; in turn, the fluorescence color of a particle can be used to identify the particle, and various materials can be “labeled” with fluorescent markers for various purposes). Another potent quantum effect of the nanoscale is known as“tunneling,” which is a phenomenon that enables the scanning tunneling microscope and flash memory for computing.

Scale at which much of biology occurs: Over millennia, nature has perfected the art of biology at the nanoscale. Many of the inner workings of cells naturally occur at the nanoscale. For example, hemoglobin, the protein that carries oxygen through the body, is 5.5 nanometers in diameter Fig. 8(C). A strand of DNA, one of the building blocks of human life, is only about 2 nanometers in diameter.

Drawing on the natural nanoscale of biology, many medical researchers are working on designing tools, treatments, and therapies that are more precise and personalized than conventional ones—and that can be applied earlier in the course of a disease and lead to fewer adverse side-effects. One medical example of nanotechnology is the bio-barcode assay, a relatively low-cost method of detecting disease-specific biomarkers in the blood, even when there are very few of them in a sample. The basic process, which attaches “recognition” particles and DNA “amplifiers” to gold nanoparticles, was originally demonstrated at Northwestern University for a prostate cancer biomarker following prostatectomy. The bio-barcode assay has proven to be considerably more sensitive than conventional assays for the same target biomarkers, and it can be adapted to detect almost any molecular target [27].

Growing understanding of nanoscale biomolecular structures is impacting other fields than medicine. Some scientists are looking at ways to use nanoscale biological principles of molecular self-assembly, self-organization, and quantum mechanics to create novel computing platforms. Other researchers have discovered that in photosynthesis, the energy that plants harvest from sunlight is nearly instantly transferred to plant “reaction centers” by quantum mechanical processes with nearly 100% efficiency (little energy wasted as heat). They are investigating photosynthesis as a model for “green energy” nanosystems for inexpensive production and storage of nonpolluting solar power [28].

Scale at which surfaces and interfaces play a large role in materials properties and interactions: Nanoscale materials have far larger surface areas than similar masses of larger-scale materials. As surface area per mass of a material increases, a greater amount of the material can come into contact with surrounding materials, thus affecting reactivity. One benefit of greater surface area and improved reactivity in nanostructured materials is that they have helped create better catalysts. As a result, catalysis by engineered nanostructured materials already impacts about one-third of the huge U.S. and global catalyst markets, affecting billions of dollars of revenue in the oil and chemical industries [29]. An everyday example of catalysis is the catalytic converter in a car, which reduces the toxicity of the engine’s fumes. Nanoengineered batteries, fuel cells, and catalysts can potentially use enhanced reactivity at the nanoscale to produce cleaner, safer, and more affordable modes of producing and storing energy. Large surface area also makes nanostructured membranes and materials ideal candidates for water treatment and desalination, among other uses. It also helps support “functionalization” of nanoscale material surfaces (adding particles for specific purposes), for applications ranging from drug delivery to clothing insulation.

V. Conclusion

Although modern nanoscience and nanotechnology are quite new, nanoscale materials were used for centuries. Alternate-sized gold and silver particles created colors in the stained glass windows of medieval churches hundreds of years ago. The artists back then just didn’t know that the process they used to create these beautiful works of art actually led to changes in the composition of the materials they were working with.

Nanoscale particles are not new in either nature or science. However, the recent leaps in areas such as microscopy have given scientists new tools to understand and take advantage of phenomena that occur naturally when matter is organized at the nanoscale. In essence, these phenomena are based on ‘quantum effects’ and other simple physical effects such as expanded surface area (more on these below). In addition, the fact that a majority of biological processes occur at the nanoscale gives scientists models and templates to imagine and construct new processes that can enhance their work in medicine, imaging, computing, printing, chemical catalysis, materials synthesis, and many other fields. Nanotechnology is not simply working at ever smaller dimensions; rather, working at the nanoscale enables scientists to utilize the unique physical, chemical, mechanical, and optical properties of materials that naturally occur at that scale.

While all of these techniques require additional research before they can be applied to humans outside of the testing lab, nanotechnology does offer hope that science can one day improve survival rates from diseases ranging from cancer to HIV and beyond.

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