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# The SAGE Encyclopedia of Theory in Science, Technology, Engineering, and Mathematics

## Nanotechnology

**By:**Carlos Eduardo Maldonado
**Edited by:** James M. Mattingly
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Nanotechnology is among the most important domains of leading-edge science and technology and is a highly promising field for future research. It deals with both theoretical and experimental structures at the nanolevel (10−9 of a meter). The origins of nanotechnology and nanoscience lie in physics, particularly the physics of condensed matter, which is the broadest of the fields of applied physics. Nanotechnology thus falls within the category of the science and engineering of materials. Significantly, in the 1 to 100 nm range, quantum effects come to bear, such as the quantum Hall effect or the Casimir quantum effect, among others.

Indeed, matter behaves differently at the macroscopic level than at the microscopic scale. Thus, a series of discoveries have been made leading to femtochemistry or femtobiology, for instance. The most important levels of the microscopic world exist at nanoscale:

- Mili = 10−3 m
- Micro = 10−6 m
- Nano = 10−9 m
- Pico = 10−12 m
- Femto = 10−15 m
- Atto = 10−18 m
- Zepto = 10−21 m
- Yocto = 10−24 m
- …
- The Planck scale = 10−33m

The Planck scale, named for theoretical physicist Max Planck (1858–1947), is the absolute limit in terms of space, beyond which—according to the current state of knowledge—nothing can be assessed. Corresponding to the Planck scale is Planck time which is 10−42 s, as the absolute limit in terms of time. The nanoscale stands out as perhaps the most exciting field in which different sciences and disciplines converge, such as physics, chemistry, engineering, mathematics, health sciences, among others.

The counterintuitive behavior of matter at the nanoscale calls attention to the structures of the atom, hence called nanoparticles. At very small scale, matter behaves differently allowing us to see quantum effects. Those quantum effects are crucial for the understanding of matter in a variety of fields and for working on quantum processes and phenomena.

The term nanotechnology was originally coined in 1974 by N. Taniguchi as a process consisting of separating, consolidating, and deforming materials by one atom or one molecule.

## Origins

Four steps can be identified regarding the origins of nanotechnology:

- The search for the structure of the microscopic world in the framework of nanotechnology can be said to have begun in 1932, when E. Ruska, a German physicist, and M. Knoll, a German engineer, built the first transmission electron microscope (TEM). The TEM made it possible to see objects at the molecular level, particularly proteins and the fine structure of metals, for it was possible to see particles smaller than 200 nm by focusing a beam of electrons rather than light through an object.
- On December 29, 1959, Richard Feynman, a leading scientist in quantum physics in general, and in quantum electrodynamics in particular, gave a talk at the California Institute of Technology (Caltech) addressed to the American Physical Society with the title “There’s Plenty of Room at the Bottom,” discussing the theoretical possibility of arranging individual atoms.
- Further on, in the 1970s, Norio Taniguchi, working at the Tokyo University of Science, coined the term nanotechnology as the process of manufacturing materials from single atoms or molecules.
- In 1986, K. Eric. Drexler published Engines of Creation. The book presents the basis for the most favorable possibilities of research in molecular technology as well as the perils and hopes of the new field. It remains as a landmark in nanotechnology and a source for those in the forefront of the

discipline.

## Key Developments

Three conceptual, technological, and methodological levels are decisive for the development of nanotechnology: microscopy, synthesis, and assembling. They are closely intertwined. The key term used in nanotechnology at large, however, is invention. Indeed, the invention of novel methods, materials, techniques, and approaches comprise the very history of nanotechnology. Briefly discussed below are some of the significant achievements of the people who have played key roles in advancing the path of nanotechnology.

The development of microscopy and its technical refinement has been crucial for the history of nanotechnology. In 1936, the field emission microscope, originally invented by Erwin Müller in Germany, made possible the near-atomic resolution images of materials. In 1981, Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope, which allowed for the first time the creation of spatial images of individual atoms. In 1986, Gerd Binnig, Calvin Quate, and Christoph Gerber invented the atomic force microscope that allows to view, measure, and manipulate materials and forces at the nanoscale.

Based on microscopy, a series of discoveries were made in a range of fields including chemistry, nuclear and quantum physics, electronics, and optics, with surprising and fruitful applications in a variety of domains. Thus, in 1981, A. Ekimov discovered nanocrystalline, semiconducting quantum dots in a glass matrix, which opened the gates for further work on electronics and optics with important impact in the health sciences. In 1985, fullerene (named after polymath and systems theorist R. Buckminster Fuller), an allotrope of carbon forming a closed or partially closed mesh, in a variety of configurations such as spheres, tubes, and ellipsoids, was discovered by H. Kroto, S. O'Brien, R. Curl, and R. Smalley who worked at Rice University (USA).

To the advances of microscopy, as mentioned, the scanning tunneling microscope and atomic force microscopy continue to deepen, enlarge, and enhance nanoscience research.

During the 1990s, nanotechnology companies begun to be established. To date, the number of companies in the field number more than 100 worldwide. In 1991, S. Lijima discovered the carbon nanotube, a structure that exhibits great properties of strength and electrical and thermal conductivity, fundamental in biological use as well as communications, and photonics. In 1991, C. T. Kresge discovered nanostructured catalytic materials MCM-41 and MCM-48, useful in water treatments, drug delivery, and other applications. Shortly afterward, in 1993, M. Bawendi at MIT invented a method for the controlled synthesis of nanocrystals. Synthesis subsequently became a key method in nanotechnology. Research along this line now influences computing, biology, and high-efficiency photovoltaics.

Along with synthesis, assembling becomes a salient feature of work in nanotechnology. In 1999, W. Ho and H. Lee were able to assemble a molecule with scanning tunneling microscopy. Little by little, similar to what was happening in the realm of genetics, in nanotechnology the work went from just reading the atom to writing it. Synthesis and assembling become regular methods and approaches that cross disciplines as varied as biology, chemistry, engineering, physics, and environmental studies.

Meaningfully, around the years 2000, several consumer products using nanotechnology began appearing in the market modifying thus imperceptibly habits and preferences. Tennis rackets, baseball bats, nanosilver antibacterial socks, cell phones, cameras, displays for TVs, therapeutic cosmetics wrinkle-resistant clothing, automobile bumpers, and many other products have been developed until to date that are smoothly but drastically changing everyday life. Nanotechnology is becoming a cultural asset in the life of society. Fifteen industrial sectors can be accounted as leaders in industry and innovation based on nanotechnology.

In 2003, Naomi Halas, Jennifer West, Rebekah Drezek, and Renata Pasqualin developed gold nanoshells for the discovery, diagnosis, and treatment of breast cancer that avoid invasive treatments. The nanoshells are tuned so that they can absorb infrared light and identify malign tumors. This is clearly a fundamental path to noninvasive medicine as well as to personalized medicine.

In 2005, Erik Winfree and Paul W. K. Rothemund made possible computations in the process of nanocrystal growth by developing theories of DNA-based computation and algorithmic self-assembly. This offered a way forward to nonconventional computation as well as to biological hypercomputation that aims to shed light on the understanding of life generally.

In 2007, Angela Belcher built a lithium-ion battery with a common type of virus nonharmful to humans. Nanotechnology could thus be identified as one key aspect for the interplay of what has been called the chip-cell interface, or the next technological singularity. Such interplay may have important consequences for future research and technology.

The pace of discoveries and achievements is relentless, indeed. Thus, in 2009 and 2010, Ned Seeman helped create several DNA-like nanoscale robotic assembly devices and DNA-assembly lines making programming self-assemble complex processes and structures.

## An Expanding Field

Nanotechnology was developed as applied science and it was so conceived for a long time. Subsequently, it has come to shed fresh light on life as well as on the materials under investigation. As such, it has morphed into the larger discipline of nanoscience.

Similar to what happened with genetics, the first period of nanotech, from roughly 1959 until the late 1990s, consisted in reading subatomic components at the nanoscale. From the 1990s until the present day, the process has included writing nanostructures: designing, synthesizing, assembling, and programming various nanoproducts and processes. Furthermore, whereas it was initially a field of interest for physicists and materials engineers, it has since deepened and enlarged its scope, encompassing also biologists, electrical and electronic engineers and computer scientists, environmentalists, and ecologists performing fundamental research on health. Only recently have some social scientists begun to join and nurture the field, thereby further enhancing its cross-disciplinary nature.

When working top-down, the study of nanotechnology moves from mechanical to thermal to optical processes, where sputtering and chemical etching are generally implemented. In other words, nanotechnology engages in the process of modifying materials in order to convert a bulk material into nanoparticles. Correspondingly, the bottom-up procedure uses atomic or molecular condensation that allows a reduction of biological structures or behaviors so that they, in turn, can lead to further chemical or electrochemical reduction. This allows the production of solid material via the sol–gel method and further to vapor deposition and the production of high-quality and high-performance solid materials.

Among the efforts to design, assemble, and program various products are those focused on developing nanorobots, either individually or also as part of swarm robotics. In medicine, they may one day be transported through the bloodstream to specific organs for cleaning up infections, eliminating tumors, or helping the immune system to produce antibodies, for example.

## Layers and Materials

Two basic types of nanotechnology materials can be identified: thin films, layers, and surfaces; and multi-layer materials including nanotubes.

Monolayers were the first materials developed and have been implemented chiefly in fields such as chemistry, engineering, and manufacture of a number of devices. Some such materials consist of one atom or are one molecule deep. Thin films and surfaces are widely produced for coating in general, pharmaceutics, and in the energy sector.

Regarding multilayer materials, layer graphene stands out for its properties that make possible increased energy capacity of rechargeable batteries as well as enhanced energy storage, flexibility, and lightweight. Current research now anticipates the development and improvement of 2D and 3D structures including silicene (an allotrope of silicon), boron, and molybdenum oxides.

In this second regard, the most conspicuous materials in nanoscience are nanotubes, which were the first materials to be developed. Made of carbon, these are cylinders of one or more layers of graphene. Usually, carbon nanotubes range from 0.8 to 2 nm and 5 to 20 nm with lengths from 100 nm to 0.5 meters. Carbon nanotubes are used in biomedical and medical research, energy storage, automotive parts, water filters, coatings, and electromagnetic fields, among other applications.

Quantum dots are man-made semiconducting nanoscale crystals that can transport electrons. When semiconductor particles are small enough, quantum effects emerge, which limit the energies at which the electrons or holes (=absence of electrons) can exist in the particles. Nanocrystals could become an important component for self-assembled nanodevices. So far, the use of quantum dots has been in artificial environments, but some research is being carried out that aims at working also in real-world environments.

Graphene, like fullerene, is an allotrope of carbon consisting of a single layer of atoms arranged in a 2D honeycomb lattice. Graphene was properly isolated and characterized in 2004. It is a zero-gap semiconductor. Among current developments are monolayer and bilayer sheets, graphene superlattices, nanoribbons, graphene quantum dots, graphene oxide, graphene fiber, aerogel, nanocoil, and many others.

Fullerene, as mentioned earlier, consists of carbon atoms connected by single or double bonds that includes a wide family of forms, structures, and shapes named for instance as C20, C60, C70 fullerene, and several others.

Nanomaterials are produced in an either of two ways, top-down and bottom-up, always as synthesis processes. In the first case, the production consists of various milling techniques to crush microparticles. Traditionally, thermal stress is involved and is energy-intensive. In contrast, bottom-up production is based on physicochemical of molecular or atomic self-organization. This method allows for better control of sizes, shapes, and ranges. Hydrothermal, sol–gel, and precipitation processes are regular practices here. Flame reactors working at temperatures around 1,200 to 2,000 °C along with plasma and laser reactors are used in industrial processes for the production of nanomaterials.

Nanorobotics is the process by which several procedures have been developed, such as nanofabrication, which produces nanomotors, nanoactuators, nanosensors, and the modeling of physical materials and processes at nanoscale. Nanorobotics comprises assembling nanometer-sized parts, the manipulation of biological cells or molecules. Rightly understood, nanorobots are nanomotors that are currently used in medicine, environmental studies, and electronics, for instance, to clear bacteria and toxins from blood or waters. Those nanomachines are activated by UV-light, DNA-origin-based nanorobots, light-induced nanotransducers, magnetic nanolink nanoswimmers, and other mechanisms and techniques. Usually, it is harder to produce nanorobots and nanomaterials than acting upon them or making them behave in a variety of ways.

## Applications

Among the fields where nanotechnology is being both developed and applied are nanobiotechnology, nanoelectronics, nanoplasmonics (research on optical phenomena at nanoscale), food and agriculture, energy, environmental preservation; various methods and techniques in biomedicine aimed at fighting HIV, cancer, Alzheimer, and food-borne illnesses; the cement industry, construction, displays, furniture, and cosmetics.

Controversy has arisen over human ability and the use of nanotechnology to gain an advantage in sports; the practice is commonly referred to as technology doping. Some sports equipment where nanotechnology is being incorporated include tennis and badminton, golf, cycling, skiing, bowling, and archery. The materials used therein encompass carbon nanotubes, silica nanoparticles, fullerenes, carbon nanofibers, nanoclay, and nano-titanium.

In cosmetics, nanotechnology is being incorporated as UV filters and in drug delivery agents. In the automotive industry, this technology is currently present in nanovarnish, carbon black in tires, solar cells, nanofilters, fuel additives, fragrance in the passenger cabin, antiglare coatings, ultrathin layers, and electrochromatic, layers, for instance.

As some observers and critics have pointed out, nanotechnology has gradually become more pervasive in everyday life, even if many people do not yet recognize it. The continuing growth of these developments will surely continue making nanotechnology and nanoscience a most salient development in the history of humankind.

## The Kavli Prize in Nanotechnology

The Kavli prize awards breakthroughs in science at the atomic scale. It is awarded every 2 years and it was established in 2008. It can be considered as the equivalent of the Nobel Prize in nanotechnology and nanoscience (Table 1).

Significantly, various awardees of the Kavli prize either had already been awarded, or will be awarded, the Nobel Prize, which is a clear sign of both the work’s prestige and scientific rigor.

**Table 1 Winners of the Kavli Prize in Nanoscience, 2008–2020**

| Name | Country | University or Laboratory | Year |
|---|---|---|---|
| Louis E. Brus | USA | Columbia University | 2008 |
| Sumio Lijima | Japan | Meijo Univeristy | 2008 |
| Donald M. Eigler | USA | IBM Almaden Research Center | 2008 |
| Nadrian Seeman | USA | New York University | 2010 |
| Mildred S. Dresselhaus | USA | MIT | 2012 |
| Thomas W. Ebbesen | France | University of Strasbourg | 2014 |
| Stefan W. Hell | Germany | Max Planck Institute | 2014 |
| Sir John B. Pendry | UK | Imperial College | 2014 |
| Gerd Binnig | Switzerland | Former member of IBM Research Laboratory | 2016 |
| Cristoph Gerber | Switzerland | University of Basel | 2016 |
| Calvin Quate | USA | Stanford University | 2016 |
| Emmanuelle Charpentier | France | Max Planck Institute | 2018 |
| Jennifer A. Doudna | USA | University of California | 2018 |
| Virginijus Siksnys | Lithuania | Vilnius University | 2018 |

| | | | |
|---|---|---|---|
| Harald Rose | Germany | University of Ulm | 2020 |
| Maximilian Harder | Austria | European Molecular Laboratory in Heidelberg | 2020 |
| Knut Urban | Germany | Max Planck Institute | 2020 |
| Ondrej Krivanek | UK and Czech Republic | R&D director at Gatan Inc., USA | 2020 |

## Science, Economics, and Politics

Finally, as it is well known, there is a scientific and political race around nanotechnology very much as it happened in the past with the exploration of outer space. The two leaders in the race are the United States and China, and the subject around which the race is defined is the course of the fourth industrial revolution in general and the role of artificial intelligence and the Internet generation 5 and 6 (5G and 6G) networks. To be sure, nanotechnology stands at the very center of the current and possible outcomes of artificial intelligence and the fourth industrial revolution. It should be mentioned that the technologies and capacities of and around nanotechnology are extremely expensive, which means that a gap will be rapidly produced between those countries with human, technical, and scientific capacities and those countries that cannot afford the costs of the competition.

Indeed, an atomic force microscope, for instance, can easily cost over half a million dollars. Of course, a good laboratory working on nanotechnology needs more than that.

Currently, there are over 1,200 research groups, laboratories, and departments in universities worldwide. In 2020, the number of private industry and private laboratories exceeded 240. There are over 340 national and international initiatives and networks. Specifically working on raw materials, there are more than 310 groups and laboratories. Currently, there are nearly 200 groups, both private and public, focused on biomedicine and the life sciences. More than 900 companies—baseball bats, cosmetics, and so on—exceeds 900.

Furthermore, regarding education and research on nanotechnology, as of 2020 there are 67 B.A. degree programs, 157 master’s degree programs, and 44 doctoral degree programs, which clearly shows both the importance and the trend of education and research in leading-edge science on nanotechnology. The number of journals either particularly focused on nanotechnology or that accept publications in the field has risen to 225, further illustrating that nanotechnology is rapidly becoming a major player in mainstream science.

See also Engineering, Contemporary; Medicine, Contemporary; Physics, Solid-State

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