Nanotechnology: Energizing Our Future

What is Nanotechnology?

Nanotechnology is the science of understanding and controlling matter at extremely tiny dimensions spanning 1 to 100 nanometers (nm). For comparison, a fingernail grows about 1 nm in a second, and there are 25,4 million nm in an inch. Matter such as gases, liquids, and solids can exhibit unusual physical, chemical, and biological properties at the nanoscale, differing in important ways from the same material in bulk. These enhanced properties include increased strength, lighter weight, more control of the light spectrum, and greater chemical sensitivity. Such phenomena result both from quantum effects, which rule particle behavior and properties at the nanoscale, and from the larger surface areas of nanomaterials. The increased surface area per mass allows more of the material to come into contact with surrounding materials. Many important chemical and electrical reactions occur only at surfaces and are sensitive to surface shape, texture, and chemical composition. Also, many nanoscale materials can spontaneously assemble into ordered structures, enabling atomic-by-atom design of materials for specific purposes. These factors make nanotechnology promising for energy applications.

Common Uses of Nanotechnology

Energy, Fuels, and Environment. With their novel properties arising from increased surface area and quantum effects, nanomaterials are used in batteries, photovoltaics, fuel cells, superconductors, solar cells, and lighting, lubricants, and semiconductors. In addition, they play a critical role in catalysts, which both speed up natural chemical reactions and enable those not readily occurring in nature. They turn raw materials such as crude oil into products like diesel fuel and help convert harmful wastes into benign compounds before they enter the environment. The superior strength of nanostructured materials is another property that makes them useful for energy use and efficiency applications. For example, carbon nanotubes, which are up to 30 times stronger than steel and only one-sixth the weight, are being incorporated into high-strength composites and woven into yarns to produce much lighter parts for cars, industrial equipment, and buildings.

Medicine. Nanoparticulate formulations of conventional drugs are being used to treat cancer and infectious diseases. Other medical applications based on nanotechnology include imaging agents and therapeutics that target tumor cells and arterial plaques, as well as new diagnostic instruments capable of detecting minute quantities of important disease biomarkers.

Electronics. Components and structural features of current integrated circuits measure 30 nm or less, dimensions at least 1,000 times smaller than typical biological cells. Every new laptop, iPad, and smart phone works on chips brimming with these nanoscale features.

Consumer Products. The use of nanomaterials in cosmetics, sunscreens, food products, and clothing is expanding. In sunblocks, the small size of these particles confers high-power protection without making skin look pasty white, and antimicrobial properties in food packaging keep food fresher and safer for longer periods. Additives to surface treatments of fabrics help them resist wrinkling, staining, and bacterial growth.

Nanoscale science, engineering, and technology focus on observing and manipulating matter at the atomic and molecular levels to create materials, devices, and systems with fundamentally new properties and functions. This research is leading to unprecedented understanding of the basic building blocks and properties of all natural and manmade things, which is depicted on the scale above.

**Scale of Things Natural and Manmade.** Nanoscale science, engineering, and technology focus on observing and manipulating matter at the atomic and molecular levels to create materials, devices, and systems with fundamentally new properties and functions. This research is leading to unprecedented understanding of the basic building blocks and properties of all natural and manmade things, which is depicted on the scale above.
Mission-Inspired Science

The energy systems of the future—whether they tap sunlight, store electricity, or make fuel from splitting water or reducing carbon dioxide—will revolve around materials and chemical changes that convert energy from one form to another such as converting light to electricity. Such materials will need to be more functional than today’s energy materials. To control chemical reactions or to convert a solar photon to an electron requires coordination of multiple steps, each carried out by customized materials with designed nanoscale structures not found in nature. Such advanced materials must be designed and fabricated to exacting standards using principles revealed by basic science.

The Basic Energy Sciences (BES) program of the U.S. Department of Energy’s (DOE) Office of Science supports fundamental research to design, observe, measure, and understand how nanoscale systems function and interact with the environment. The Nanoscale Science Research Centers (NSRCs) are DOE’s premier user facilities for interdisciplinary research at the nanoscale. New scientific understanding and technologies emerging from the NSRCs, as well as the BES Energy Frontier Research Centers, have the potential to transform understanding of energy and matter and to advance national, economic, and energy security. Select examples of these discoveries are highlighted below.

Nanoscale Dynamics: Ultrafast Transformations

Molecules are constantly vibrating and reorienting themselves. Chemical reactions happen in an instant, when an atom is captured by or freed from a molecule. All these things occur in mere quadrillions of a second called a femtosecond (fs). Photographically, for example, it is a natural limit of processes that transfer light into chemical energy that easily stored and transported. To understand such complex reactions, researchers must be able to observe them at the timescales on which they occur, and better understanding could lead to new materials that perform similar functions.

Meoscale Science: Bridging from Atom to Bulk

In many technologically important materials, the functionality critical to macroscopic behavior begins to manifest itself not at the atomic or nanoscale, but at the mesoscale. New features arise during transition to this dynamic, intermediate regime, which straddles the small scale of individual atoms and large scale of collective systems. These features include the emergence of collective behavior: interaction of disparate electronic, mechanical, magnetic, and chemical phenomena; appearance of defects, interfaces, and statistical variation; and self-assembly of functional composite systems.

Solar Panel Progression

Atomic-level structure of a cathode battery material

Atomic-level structure of a multifunction solar cell

Microstructure of a cathode material on an aluminum conductor

Cross-section of a composite cathode material and separator laminate, ready for cell assembly

Laminated cathode and anode materials and separator laminate, ready for cell pack manufacturing

Commercial pouch type lithium ion battery for high-energy applications

How Fast Is Ultrafast?

NATURE

Hummelbing wing motion (~1 ms)

Camera shutter speed (~1 ms)

Canoe throw (~1 ms)

Magnetic recording time (10 s–10 min)

Protein folding (~10 ps)

Computing time (10 s–10 min)

Average collision time between molecules (~30 ps)

Dissipation of light (~100 fs)

Light travels 300 nm (length of a virus) in 1 fs

Understanding phase transformations has important implications for the future design of hydrogen storage systems, catalysts, fuel cells, and batteries. Recent research demonstrates that as metal nanocrystals go through such transformations, size can make a much bigger difference than previously thought. A unique optical probe based on luminescence provided the first direct observations of metal nanocrystal undergoing phase transformations, which promise to improve such materials with hydrogen, revealing a surprising degree of size dependence for such critical properties as thermodynamics and kinetics.

Scientific User Facilities

U.S. Department of Energy, Office of Science
Office of Basic Energy Sciences

Nanoscale Science Research Centers
Center for Functional Nanomaterials
Brookhaven National Laboratory, New York
Center for Integrated Nanotechnologies
Sandia National Laboratories and Los Alamos National Laboratory, New Mexico
Center for Nanophase Materials Sciences
Oak Ridge National Laboratory, Tennessee
Center for Nuclear Materials Sciences
Argonne National Laboratory, Illinois
Molecular Foundry
Lawrence Berkeley National Laboratory, California


How Fast Is Ultrafast?

NATURE

Hummelbing wing motion (~1 ms)

Camera shutter speed (~1 ms)

Canoe throw (~1 ms)

Magnetic recording time (10 s–10 min)

Protein folding (~10 ps)

Computing time (10 s–10 min)

Average collision time between molecules (~30 ps)

Dissipation of light (~100 fs)

Light travels 300 nm (length of a virus) in 1 fs

Understanding phase transformations has important implications for the future design of hydrogen storage systems, catalysts, fuel cells, and batteries. Recent research demonstrates that as metal nanocrystals go through such transformations, size can make a much bigger difference than previously thought. A unique optical probe based on luminescence provided the first direct observations of metal nanocrystal undergoing phase transformations, which promise to improve such materials with hydrogen, revealing a surprising degree of size dependence for such critical properties as thermodynamics and kinetics.

Scientific User Facilities

U.S. Department of Energy, Office of Science
Office of Basic Energy Sciences

Nanoscale Science Research Centers
Center for Functional Nanomaterials
Brookhaven National Laboratory, New York
Center for Integrated Nanotechnologies
Sandia National Laboratories and Los Alamos National Laboratory, New Mexico
Center for Nanophase Materials Sciences
Oak Ridge National Laboratory, Tennessee
Center for Nuclear Materials Sciences
Argonne National Laboratory, Illinois
Molecular Foundry
Lawrence Berkeley National Laboratory, California