Nanotechnology
Energizing Our Future

Energy is critical to all aspects of daily human activities and the economy. With world demand expected to double by 2050, science innovations are key to providing environmentally sustainable energy sources. By exploring matter at its tiniest, nanoscale science offers great potential for delivering a range of these innovations—from tapping unused sun and wind energy to storing electrical energy at high density. Also possible are the efficient use of energy in solid-state lighting and fuel cells and the production of electricity from advanced coal and nuclear power sources that emit no carbon dioxide. Because all the basic steps of energy conversion (e.g., charge transfer, molecular rearrangement, and chemical reactions) take place at the nanoscale, high-performing nanomaterials could help transform the way energy is produced, stored, and consumed.

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. This 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 atom-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, solid-state lighting, lubricants, and thermoelectrics. 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 gasoline or plastics 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 promising 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.

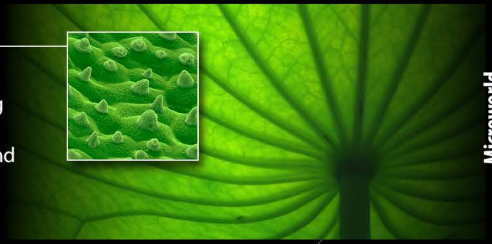
Consumer Products. The use of nanomaterials in cosmetics, sunscreens, food products, and clothing is expanding. In sunblocks, the small size of these particles confers high-power protection without making skin look pasty white, and antimicrobial properties in food packaging keep food fresher and safer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

Biomimetics. Designing, synthesizing, and engineering substances that mimic or improve natural products based on studies of the formation, structure, and function of biologically produced compounds and materials (e.g., enzymes and silk) and processes (e.g., protein synthesis and photosynthesis).

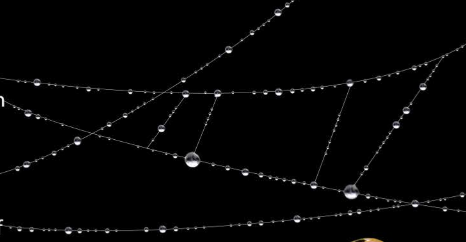
Shark skin scale
(~60 to 120 µm thick; width of a human hair)
The tooth-like scales of shark skin are ribbed with longitudinal grooves. This design allows water to move efficiently over their surface, enabling sharks to swim at high speeds with low energy input. Plastic film coatings with this same microscopic texture could, for example, reduce vehicle drag.

Honey bee
(~14 mm long)

Pollen grain
(~5 to 200 µm in diameter)
Depending on the pollen source, a bee can collect more than a million grains in its pollen basket during a single foraging trip.

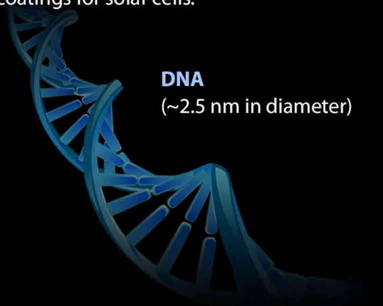


Lotus leaf surface
(protusions ~5 µm in diameter and ~10 µm apart)
A lotus leaf's rough, wax-coated surface allows water droplets to remain almost spherical, rolling freely in all directions while picking up dirt particles. Such superhydrophobic surface characteristics could be used in energy conversion and conservation processes and in micro- and nanofluidic applications to reduce drag in fluid flow.

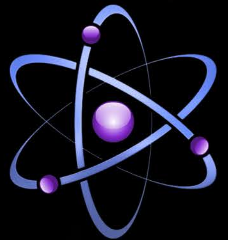


Spiderweb silk strand
(3 to 8 µm wide)
Pleated sheets of nanocrystals are connected by weak hydrogen bonds and embedded in protein strands, giving spiderweb silk both flexibility and high tensile strength. Under low stress, the protein strands uncoil and straighten; under greater stress, the load gets transferred to the nanocrystals. If necessary, some of the hydrogen bonds slip, allowing the structure to stretch without breaking. Understanding of these properties is leading to the development of various materials and fibers with high mechanical strength.

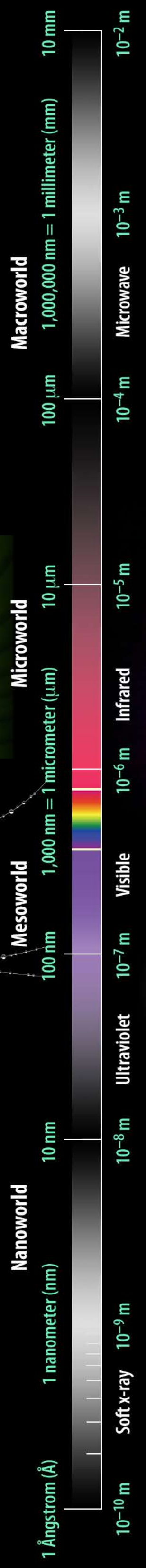
Moth eye surface
(bumps ~50 to 300 nm in diameter)
The film on the surface of insect compound eyes consists of thousands of closely packed nanoparticles. These nonreflective structures that allow moths to see well in the dark without attracting predators have inspired new antireflective coatings for solar cells.



DNA
(~2.5 nm in diameter)

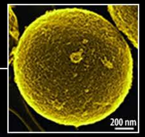


Atom
(1 Å = 0.1 nm in diameter)

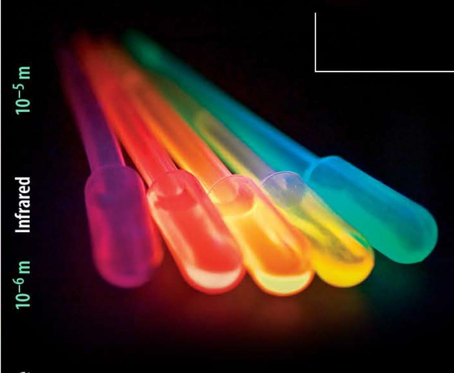


Nanofabrication. Fabricating customized materials with atom-by-atom precision to create new opportunities for revolutionizing, for example, future energy systems. These approaches are based on scientific studies of how materials assemble at the nanoscale.

Microelectromechanical systems (MEMS) device
(10 to 100 µm wide)
Tiny gears increase the torque of a micromechanical motor. By placing the gearing and motor on the same chip as the integrated circuit that controls them, machines can be made practically invisible to the naked eye. Applications for MEMS devices include sensors, microresonators, infrared detectors, missile defense, fuel cells, and magnetic data storage systems.

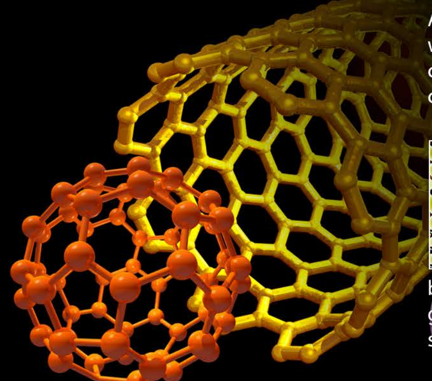


Titanium oxide bronze nanoparticle
(~1 µm in diameter)
Such particles form a promising battery electrode material because each titanium oxide bronze sphere contains 10 to 20 nm-size pores.

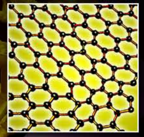


Quantum dots
(~100 to 500 nm in diameter)
Quantum dots are semiconducting nanoparticles that can produce a rainbow of colors. The wavelength, or color, of light that quantum dots emit can be tuned simply by changing their size, a feature offering great potential for applications such as light-emitting diodes, solid-state lighting, lasers, and solar cells. Quantum dots already are being used as fluorescent labels for biological imaging.

Molecular transistor
(electrode spacing [active region] ~10 nm)
Electrodes created with electron beam lithography and linked with a carbon nanotube form a molecular transistor. Transistors are electronic switching devices where a small amount of electricity is used like a gate to control the flow of larger amounts. In computers, the more transistors, the higher the performance. With one of the thinnest fabricated electrical wires, this nanotube device is one of the smallest transistors possible.



Carbon nanotube
(~1.3 nm in diameter)
A carbon nanotube is essentially a rolled-up sheet of graphene whose properties vary depending on how the sheet is rolled. They can be used for a wide range of new and existing applications from composite coatings to ultracapacitors to improved batteries.



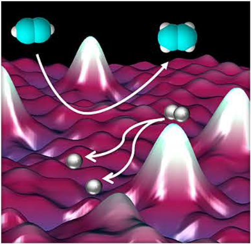
Graphene
(~1 Å thick = 0.1 nm)
A computer simulation shows the molecular structure of graphene, a single layer of graphite composed of hexagonally arranged carbon atoms (spheres) linked by strong covalent bonds (rods). Strong, flexible, and lightweight, graphene efficiently transports electrons and may one day replace silicon in computer chips and other technology applications.

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, some of which are depicted on the scale above.

Mission-Inspired Science

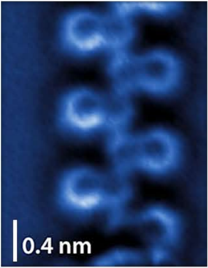
The energy systems of the future—whether they tap sunlight, store electricity, or make fuel from splitting water or reducing carbon dioxide—will revolve around materials and chemical changes that convert energy from one form to another such as converting light to electricity. Such materials will need 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.



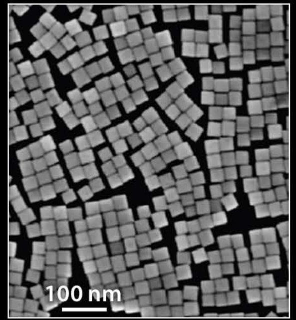
Scanning tunneling microscopy image depicting atomically dispersed Pd atoms on a Cu surface. The Pd atoms activate hydrogen, and the Cu sites insert it into acetylene, enabling the industrially important conversion of acetylene to ethylene to proceed with extraordinary selectivity.

Catalytic hydrogenations are critical to many industries. In petroleum refining, for example, they are performed to produce hydrogen-rich products like gasoline. Typical heterogeneous hydrogenation catalysts involve nanoparticles composed of expensive noble metals or alloys based on platinum, palladium (Pd), rhodium, and ruthenium. To reduce costs and potentially increase reactivity, researchers are studying the catalytic activity of single atoms. In one study, researchers coated the catalytically inert surface of the inexpensive metal copper (Cu) with single Pd atoms, which yielded an ultraselective catalyst. By controlling changes to the amount and geometry of the atomically dispersed metal, catalyst selectivity and activity can be fine-tuned with ultimate precision.



Noncontact atomic force microscopy image of a molecular chain's chemical structure, enabling accurate ab initio *modeling and determination of the molecular chain's electronic structure.*

Semiconducting conjugated polymers are attracting significant interest for applications in light-emitting diodes, field-effect transistors, photovoltaics, and nonlinear optoelectronic devices. Central to the success of these functional organic materials is the facile tunability of their electrical, optical, and magnetic properties, along with easy processability and outstanding mechanical properties associated with polymeric structures. Scientists have developed a technique for covalently bonding some particular building blocks into polymer-like chains using a flexible cyclization process, revealing a new molecular self-assembly process. This technique paves the way toward fabrication of new covalently coupled molecular machine structures on various surfaces (including metals and insulators).



Scanning electron micrograph of palladium nanocubes with a side length of about 32 nanometers.

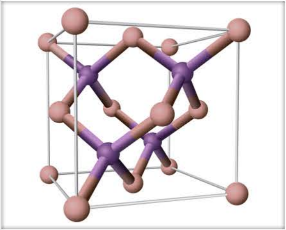
Understanding phase transformations has important implications for the future design of hydrogen storage systems, catalysts, fuel cells, and batteries. Recent research demonstrates that as metal nanocrystals go through such transformations, size can make a much bigger difference than previously thought.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

Mesoscale Science: Bridging from Atom to Bulk

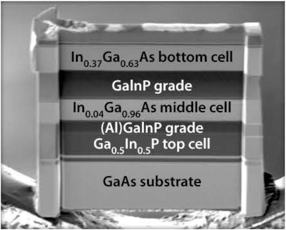
In many technologically important materials, the functionality critical to macroscopic behavior begins to manifest itself not at the atomic or nanoscale, but at the mesoscale. New features arise during transition to this dynamic, intermediate regime, which straddles the small scale of individual atoms 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.

Manipulation and control of mesoscale architectures take nanotechnology a step further toward discovery, design, and enhancement of complex phenomena and functionalities and, ultimately, new technologies. For example, light can be manipulated in photonic crystals, metamaterials, and surface plasmon polaritons to promote chemical reactions, harvest energy from sunlight, and enhance the performance of light-emitting diodes. New generations of electrodes for batteries and fuel cells can be designed to promote the coordinated motion of electrons, ions, and gases and to maximize efficiency and energy density. Mesoporous membranes with functionalized charge and chemical profiles lining the pores can be designed to separate carbon dioxide, purify water, and catalyze chemical reactions.

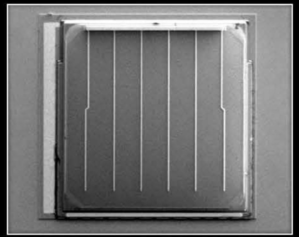
Solar Panel Progression



Atomic-level structure of gallium arsenide semiconductor



Ion beam cross-section of a multijunction solar cell

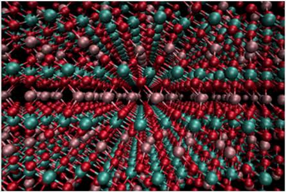


Stacked solar cell

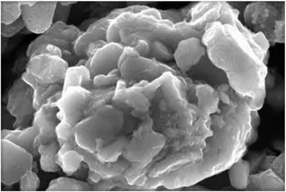
Minimodule containing microlenses

Solar panel

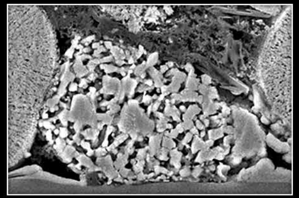
Battery Progression



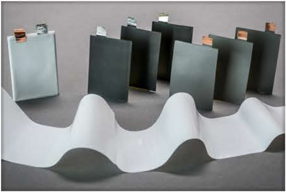
Atomic-level structure of a battery cathode material



Microstructure of a cathode material



Cross-section of a composite cathode material on an aluminum conductor



Laminated cathode and anode materials and separating membrane, ready for pouch cell assembly

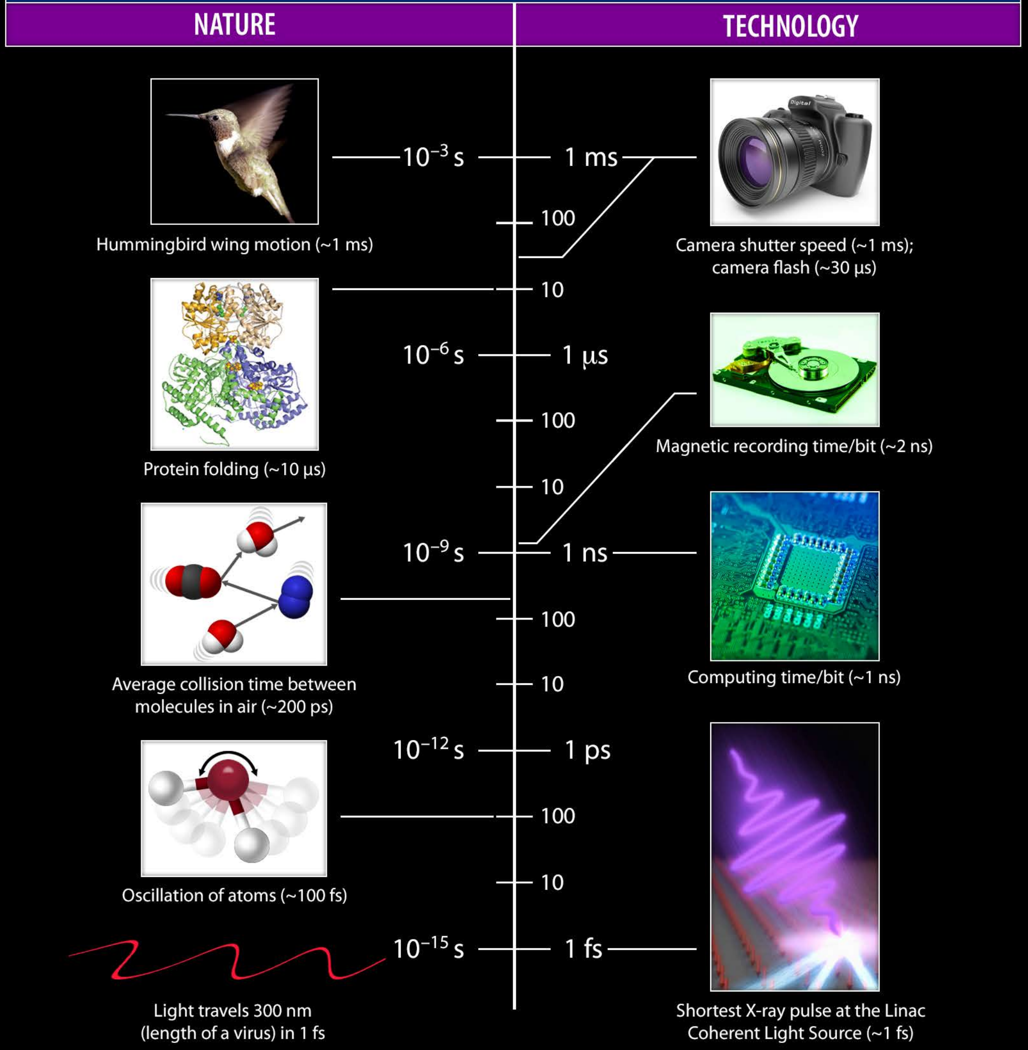
Commercial pouch-type lithium-ion battery for high-energy applications

Image credits. Front: Sunset, cityscape, honey bee, batteries, lotus leaf, smart phone, moth, DNA strand, and atom (iStock). Shark skin scales (Visual Photos). MEMS device (Sandia National Laboratories). Titanium oxide bronze nanoparticle (Oak Ridge National Laboratory). Lotus leaf surface, molecular transistor, and carbon nanotube (Science Photo Library). Quantum dots [Argonne National Laboratory (ANL)]. Moth eye surface (Visuals Unlimited). Graphene [Lawrence Berkeley National Laboratory (LBNL)]. **Back:** STM of Pd atoms (Charles Sykes, Tufts University). NC-AFM of molecular chain [Riss et al. 2014. DOI: 10.1021/nl403791q (CC-BY 4.0)]. SEM of Pd nanocubes (Bardhan et al. 2013. DOI: 10.1038/NMAT3716. Reprinted by permission of Nature Publishing Group). Multijunction solar cell (Geisz et al. 2008. DOI: 10.1063/1.2988497. Reprinted by permission of AIP Publishing LLC). Stacked solar cell and minimodule (Sheng et al. 2014. DOI: 10.1038/NMAT3946. Reprinted by permission of Nature Publishing Group). Solar panel (Semprius, Inc.). Battery progression images (Joint Center for Energy Storage Research, ANL). Hummingbird, camera, computer hard drive, and microprocessor (iStock). Protein structure (LBNL). X-ray pulse (SLAC National Accelerator Laboratory).

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 quadrillionths of a second called a femtosecond (fs). Photosynthesis, for example, is a natural ultrafast process that converts sunlight into chemical energy that is 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.

How Fast Is Ultrafast?



Scientific User Facilities

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

Molecular Foundry

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 Nanoscale Materials
Argonne National Laboratory, Illinois

Molecular Foundry
Lawrence Berkeley National Laboratory, California

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