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 mm 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 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 the bioelectronics. 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 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 and efficient 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 fresh and safer for longer periods. Additives to surface treatments of fabrics help them resist wrinkling, staining, and bacteriostatic.

**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).

**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.

**Things Natural**

- **Shark skin scale** (100 μm thick—width of a human hair)
- **Lotus leaf surface** (protrusions ~5 μm in diameter and ~10 μm apart)
- **Spider silk** (10 μm wide)
- **Moth eye surface** (bumps ~30-100 nm in diameter)

**Things Mannmade**

- **Microelectromechanical systems (MEMS) device** (10 μm thick, 10 μm long)
- **Tin-oxide-cadmium-mercury** (1 μm in diameter)
- **Quantum dot** (~100 to 500 nm in diameter)
- **Carbon nanotube** (~1.4 nm in diameter)
- **Graphene** (~1 A thick, 0.1 nm)}
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 Center, 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 quadrillionths of a second called a femtosecond (fs). Photovoltaics, for example, is a natural way to process that femtosecond light 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?**

<table>
<thead>
<tr>
<th>NATURE</th>
<th>TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hummingbird wing motion (~1 ms)</td>
<td>Camera shutter speed (~1 ms)</td>
</tr>
<tr>
<td>Protein folding (~10 ps)</td>
<td>Magnetic, recording time (hr) (~1 ns)</td>
</tr>
<tr>
<td>Average collision time between molecules (hr) (~24 ps)</td>
<td>Computing time (hr) (~1 ns)</td>
</tr>
<tr>
<td>Oscillation of atoms (~100 fs)</td>
<td>Light travels 300 nm (length of a virus) in 1 fs</td>
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**Mesoscale Science: Bridging from Atom to Bulk**

In many technologically important materials, the functionality critically depends on the macroscopic behavior 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 a photonic crystal, 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. Membranes with functionalized charge and chemical profiles, like ion 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 multifunction solar cell
- Stacked solar cell
- Minimodule containing microsensors
- Solar panel

**Battery Progression**

- Atomic-level structure of a battery cathode material
- Microstructure of a composite cathode material on an aluminum conductor
- Cross-section of a composite cathode material and separate graphene, ready for micromolding of cell assembly
- Laminated cathode and anode materials and separator geometry, ready for high-energy pouch cell assembly
- Commercial pouch type lithium-ion battery for high-energy applications

**Scientific User Facilities**

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

Nanoscale Science Research Centers
- Center for Functional Nanomaterials
- Center for Integrated Nanotechnologies
- San Diego National Laboratories and Los Alamos National Laboratory
- New Mexico
- Center for Nanophase Materials Sciences
- Oak Ridge National Laboratory
- Center for Molecular Foundry
- Lawrence Berkeley National Laboratory

Molecular Foundry
- Lawrence Berkeley National Laboratory, California