NANOSCIENCE
How to Invent a Whole New Field

In 1959, the famed physicist Richard Feynman gave a lecture that proved unusually prophetic. In it, he declared that there was "plenty of room at the bottom," meaning there were huge opportunities for new science and important new technologies by exploring and manipulating materials almost literally atom by atom. Today that "room at the bottom" is called nanoscience, and is an important part of research in physics, chemistry, materials science, and biology. Moreover, you can literally see the impact of this research on TV. The current generation of video screens made by Samsung, Sony, and others use a U.S.-developed nanotechnology called *quantum dots* to create very high-resolution images with increasingly precise, vivid colors.

But there wasn't a clear path leading from Feynman's vision to a well-developed area of science and to commercial technologies now embedded in a growing number of industrial, military, and consumer products. Rather it required a mix of discovery, strategically planned basic research, and both government- and industry-supported applied research. As the semiconductor industry pushed to make transistors and other electronic components ever smaller, for example, they eventually reached the nanoscale regime—smaller than 100 nanometers. At such scales, 1,000 times smaller than the width of a human hair, materials behave quite differently. The industry had to develop ways to understand and cope with these behaviors.

Quantum dots are tiny semiconductor crystals less than 100 atoms in width, yet this nanotechnology makes greens and reds pop on quantum dot displays (left) compared with conventional LCD displays (right). *(Nanosys, Inc.)*

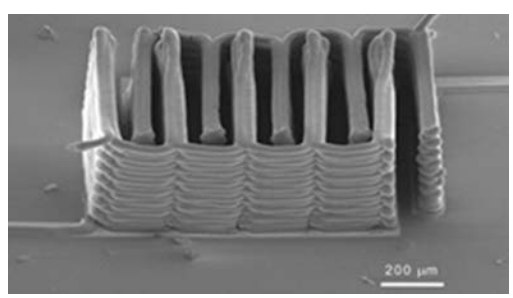
BES-funded nanoscale research centers provide advanced analytical tools and contaminant-free facilities—often called clean rooms—for materials synthesis, enabling scientists from many universities to study nanoscale phenomena.
(Lawrence Berkeley National Laboratory)

In addition to the semiconductor industry's top-down approach, the research community began in the late 1980s to investigate nanoscale phenomena from the bottom up, growing materials while precisely controlling their composition and structure almost atom by atom.

By 1999, the potential for nanoscience and nanotechnology was clear and became a national priority, leading to a presidential National Nanotechnology Initiative in 2001. But few university laboratories could afford the advanced analytical tools and contaminant-free facilities for materials synthesis that were needed to study nanoscale phenomena. So DOE's Basic Energy Sciences (BES) office proposed and supported the creation of five Nanoscale Science Research Centers as an addition to existing shared research facilities. These were located at DOE National Laboratories to enable access to existing X-ray and neutron probes and advanced computing tools. In the decade since they came into full operation, the centers have transformed and greatly broadened nanoscience research, providing access to advanced equipment and support staff, and facilitating broad interdisciplinary integration—from materials science to biology to engineering. In 2016, for example, the centers hosted and supported more than 3,000 different scientific teams.

The bottom-up approach has also led to significant commercial technologies. Work in several laboratories had led to the discovery of quantum dots—tiny crystals of semiconductors typically smaller than 10 nanometers—that could emit light of a single wavelength when stimulated with electricity. But it was not until the 1990s that researchers supported by BES at Lawrence Berkeley National Laboratory developed ways to produce and study quantum dots as small as 50 atoms wide. They discovered that the color of the emitted light depended on the size of the crystal—larger ones gave off red light, smaller ones blue light—and they developed chemical methods to reliably control crystal size. They also discovered how the shape of the crystals controlled their electrical and optical properties. Later, U.S. companies Nanosys and Quantum-Dot Corporation built on that knowledge and supported applied research (at BES shared research facilities and in their own laboratories) to industrialize production of quantum dots, embed them in a plastic supporting matrix, and integrate them into the technology of video displays. That in turn led to their commercialization in the current generation of large, very high-resolution TV screens.

Another more recent example is BES-supported research into materials that can be made into inks for 3-D printers, which in turn can be used to print antennas for use in mobile phones, circuit parts for the emerging field of flexible electronics, and extremely tiny lithium batteries. The antennas, for example, are made from a novel silver ink and are formed by printing tiny silver particles to build up a 3-D antenna shape that occupies only one-tenth the area of a flat antenna on a printed circuit board. The lithium batteries, created by printing two different nano-particle inks, are literally the size of a grain of sand (see photo). In fact, the combination of smaller size, lower cost, and greater ease of manufacture makes these and other 3-D printed devices of interest for myriad applications. Major companies like Applied Materials are getting involved.



Lithium ion microbattery the size of a grain of sand, created by Jennifer Lewis at Harvard with a 3-D printer using two types of novel nanoscale inks. *(Jennifer Lewis / Harvard University)*

The nanoscale shared research facilities have also led development of new tools for nanoscience, including advances that have enabled the world's most powerful electron microscopes (see box). These tools and the growing sophistication of techniques for synthesizing nanoscale materials are expected to lead to improved nanotechnologies. Examples include new photovoltaic materials that could capture sunlight with higher efficiencies and at lower cost, or the development of nanowires only a few atoms in width that could create still smaller but more powerful computer chips and electronic devices. Recent work at the nanocenters has also helped create advanced versions of metal organic frameworks—lattices of metal atoms, connected by organic molecules—with unusual properties that may lend themselves to the storage of hydrogen fuels.

Looking further ahead, scientists are already investigating nanotechnologies that could increase tenfold the density of data storage, provide an improved basis for quantum computing, and enhance data security on widespread networks of sensors. Particles of metal at the nanoscale may have unique catalytic properties, which would be valuable for the petrochemical industry. Nanometer-scale particles that are coated with biomolecules are already being used for cancer chemotherapy.

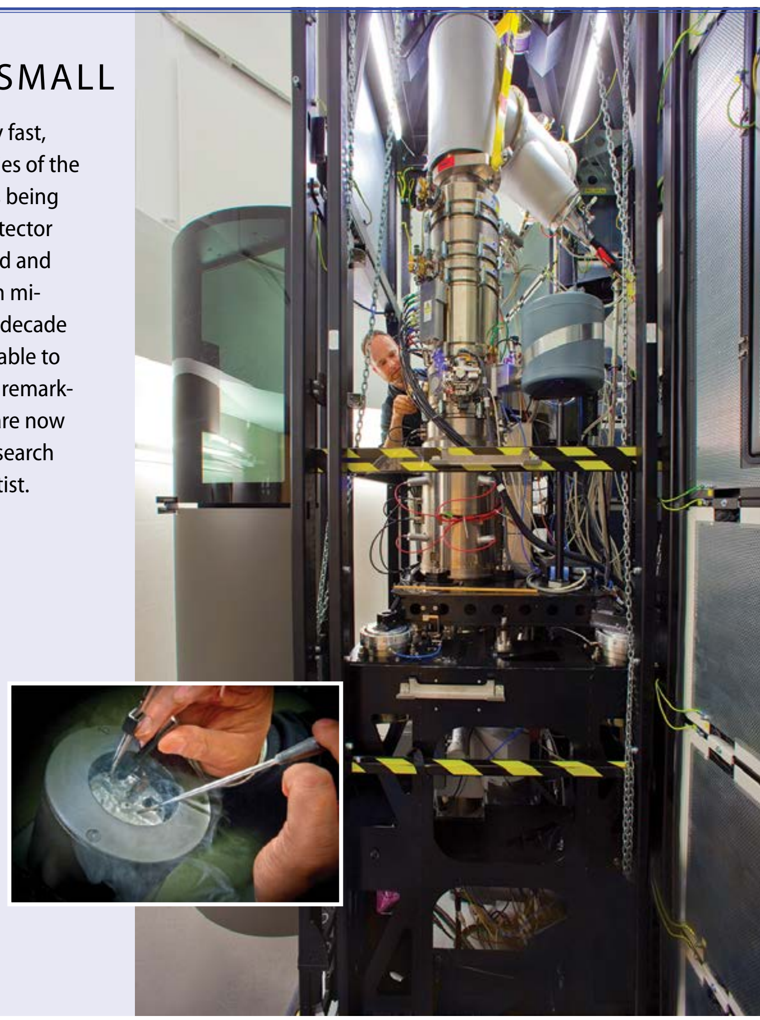
It seems Feynman was right—there was lots of room for nanoscale innovation, and nanoscale science remains fundamental to progress in almost every area of technology.

Box

SEEING OBJECTS THAT ARE INFINITELY SMALL

The 2017 Nobel Prize in Chemistry was awarded to the developers of cryo-electron microscopy, which enables researchers to examine the structure of extremely small, nanoscale objects. The microscope creates images with a stream of electrons, which enable it to "see" things much smaller than are visible with light. And because the microscope works with frozen samples, it allows scientists to study stop-action images of physical or biological processes (such as a virus in the process of infecting a human cell).

The critical technology that enabled this powerful new kind of microscopy is a method of electronically detecting individual electrons reflected from a sample of interest—in effect, a digital camera that works with electrons rather than light. It was developed by a team of scientists from Lawrence Berkeley National Laboratory in California and from the BES-supported nanoscale shared research facilities. The camera captures multiple 2-dimensional images of the sample, and then digitally synthesizes them into a 3-dimensional image for scientists to analyze. Because the electron detectors are also very fast, the camera can even take movies of the sample, illustrating the process being studied. The BES-supported detector technology was commercialized and incorporated into cryo-electron microscopes, which after about a decade of improvements have proved able to "see" nanoscale phenomena in remarkable detail. Such microscopes are now standard equipment at DOE research facilities, available to any scientist.



Cryo-electron microscopes such as the one shown here, developed by LBNL and the nanoscale research centers, are the most powerful in the world because they capture images with electrons, not light. Samples are frozen in a super-cooled container (inset), allowing scientists to study biological or physical phenomena in process. *(Lawrence Berkeley National Laboratory)*