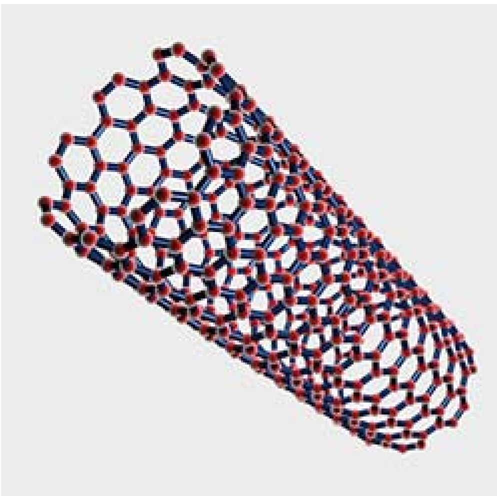
The big deal about small

By Paul Spinrad

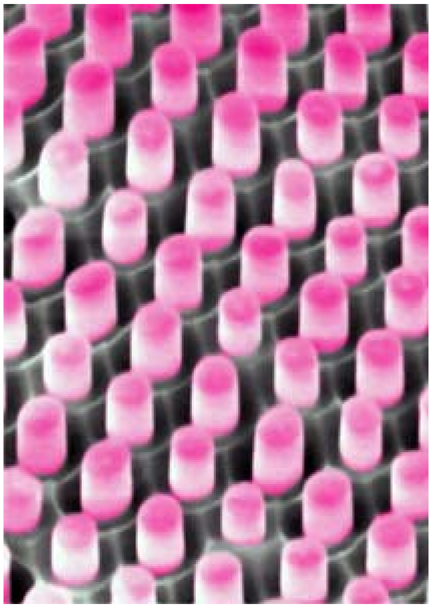


Carbon nanotubes measure only a few nanometers in diameter. With their extraordinary strength, efficient thermal conductivity and high surface-area-to-volume ratio, they have multiple potential applications in electronics, optics and materials science.

In first-year physics, students learn that atoms change their level of excitation as their orbiting electrons jump between higher and lower level orbits. They also learn that each element emits a characteristic mix of colors based on its set of possible electron jumps. This is the element's emission spectrum, and it's roughly the same for a bulk sample of that element as it is for an individual atom.

But, at a small enough scale—below a certain quantum limit—a collection of atoms no longer exhibits this bulk behavior. Its emission spectrum depends on the number and arrangement of atoms it contains, and adding or subtracting a single atom changes the colors it emits. By fine-tuning the composition of these quantum dots, engineers can make them give off any colors they want. It's the same for other properties of matter: strength, sonic properties, chemical behavior, electrical conductivity. Working at these scales, the old rules no longer apply. Here, it's possible to get behind the curtain of reality and work with a more fundamental and flexible palette of possibilities.

This is the power of nano. In literal terms, nano simply refers to things on the scale of a nanometer, one billionth of one meter. But what excites the nearly 100 UC Berkeley faculty now working in nano research isn't just going smaller. It's using unique nanoscale properties to create materials and devices that have the capacity to do the previously impossible.

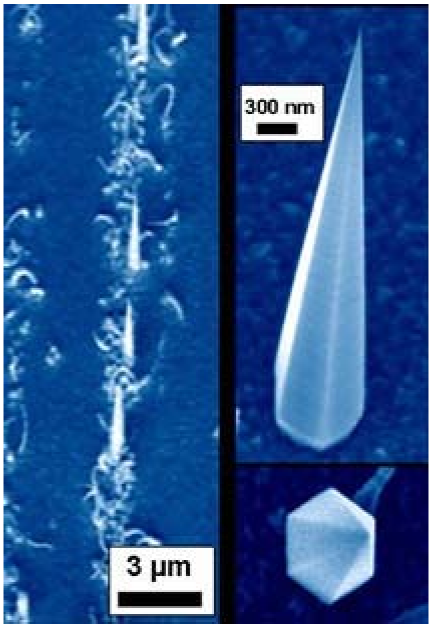


This scanning electron microscopic image of single-crystalline nanopillar cells of optically active semiconductor on aluminum substrate, grown by Ali Javey (EECS) and his team, could facilitate production of highly efficient and cost-effective photovoltaic solar cells. COURTESY ALI JAVEY

Nanotechnology emerged in the late 1980s, when physicists first visualized molecules with scanning microscopes and chemists discovered carbon molecules with new shapes like buckyballs and nanotubes that had unique properties. The concept of nano was first articulated in 1959 by American physicist Richard Feynman, the term first used in 1974 by Japanese electrical engineer Norio Taniguchi, and the idea exposed to the popular consciousness in 1986 by American molecular scientist and engineer Kim Eric Drexler.

These origins bear witness to the interdisciplinary roots of nano research, which at Berkeley involves several specialized groups uniting faculty from chemistry and physics, bioengineering, materials science and other departments. Coordinating these efforts is BNNI, **Berkeley Nanosciences and Nanoengineering Institute**, the umbrella organization for campus nano research, especially on the non-biomedical side. (Life sciences–based nano research is covered by QB3, the **California Institute for Quantitative Biosciences.)**

"At their core, nanoscience and nanotech are interdisciplinary," explains BNNI director Ramamoorthy Ramesh, also professor of materials science & engineering and physics. "You need chemists who can synthesize the materials at this scale, physicists who can probe their properties, theorists who can build predictive models for their behavior and engineers from multiple disciplines who can put them into platforms." Enthusiasm for nano at Berkeley Engineering is high and, not surprisingly, the campus has been ranked consistently at or near the top among research universities by the micro and nanotech trade magazine *Small Times.*



This gallium arsenide nanoneedle is the sharpest point she's seen, says Connie Chang-Hasnain (EECS), who discovered it on silicon while exploring methods to monolithically integrate dissimilar single crystals. The nanoneedle has the capacity to convert single photons into more than 100 cascades of electrical charge, giving them potential as both optical detectors and solar cells. COURTESY CONNIE CHANG-HASNAIN

"Given the bandwidth at Berkeley, it's one of the largest nano research efforts," Ramesh says. Berkeley's program benefits from its proximity to, and overlaps significantly with, Lawrence Berkeley National Lab (LBNL). Much of the funding for nano research comes from federal sources, including the National Science Foundation, the Departments of Energy and Defense and the National Institutes of Health, as well as the semiconductor and biomedical industries.

How do you make such small objects in the first place? Top-down techniques such as photolithography can create structures like Intel's newest microprocessors, with printed wires measuring 45 nanometers wide. But, just as biochemists create organic and organically inspired macromolecules in solution, most nano building blocks are synthesized chemically, with single-molecule tubes, spheres and larger nanocrystals and nanowires grown in solution or through vapor deposition. Polymer nanofibers can be squirted and spun out like spider's silk.

Components at the nanoscale are made in clean, controlled environments like the new **Marvell Nanofabrication Lab** in Sutardja Dai Hall and LBNL's **Molecular Foundry.** The clean rooms prevent dust from interfering with production and keep nanoparticles out of the environment for safety reasons. Although nanoscale carbon forms occur naturally in soot, and carbon nanotubes can damage lung tissue if inhaled, little is known about the possible hazards of nanoengineered materials and how they behave in the environment. Nano research at Berkeley and other major research centers is heavily regulated and complies with state and federal occupational health and safety regulations.

Nanotechnology has already hit the marketplace in the form of such products as stain-resistant fabrics, protective coatings in paints, and cosmetics with colloidal nanoparticles that help bind the product to skin. In biomedicine, nano-enabled anticancer therapies are already in clinical trials, and some types of tissue regeneration could become reality in the next few years. Microprocessor chips based on nanostructures are still several years off, but traditional top-down semiconductor fabrication techniques have already reached the nanometer scale.

A full account of nano research on the Berkeley campus would require volumes, but here's a nanoscale summary of three strong areas.

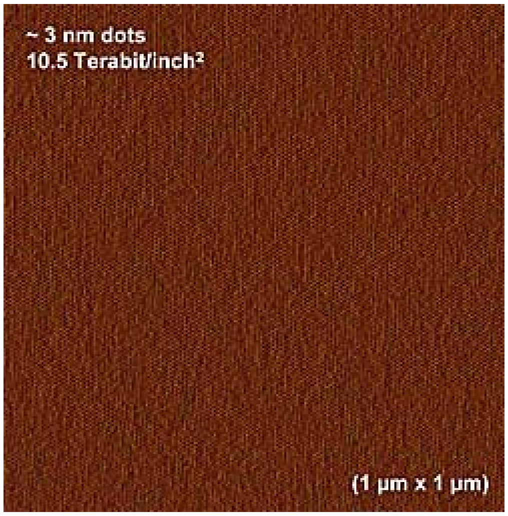
Information technology

In the semiconductor industry, it's nano or bust. Chips have been getting smaller and more powerful for decades, but the manufacturing process is approaching its physical limits. The only way to break those barriers will be some form of nanotechnology.

Carbon nanotubes: One leading concept is to build microprocessors out of carbon nanotubes, nanostructures engineered to store data and perform logic operations. Current methods of producing them are difficult to control, but Ming Wu (EECS) and colleagues at the Berkeley Sensor and Actuator Center are working on electrostatically controlled and laser-powered "nanotweezers" that could sort and assemble components into circuits at high speed.

DNA scaffolds: Jeffrey Bokor (EECS) and others use custom DNA strands that attach only to matching strands to create "smart-tape" scaffolds for nano self-assembly. By designing a sequence of liquid washes, DNA strands and chemicals that link the two together, it's possible to mass assemble arbitrary numbers of nanostructures in parallel. Refinements are still needed, but as the library of linker chemicals grows and improves, this method will support more complex assemblies.

Beyond electricity: Farther out, nanocomputers might not even be based on electricity; any other characteristic of matter and energy that has two states can represent logic. Researchers Connie Chang-Hasnain and Eli Yablonovitch (both EECS) are working on nanocomputing and networking using light rather than electrons. Alex Zettl (Physics) has demonstrated a rewritable memory element based on the physical position of an iron nanoparticle inside a multi-walled carbon nanotube that, packed densely, would store more information and last longer than current flash memory. Jeffrey Bokor (EECS) and others are investigating spintronics—computing based on particle spin direction—and other phenomena like mechanical deformation and magnetism that might consume less energy and generate less waste heat than electronics.



This atomic force microscope image shows a highly ordered arrangement of nanoscale dots, each just 3 nanometers in size. The ultra-dense material, the work of Ting Xu (MSE) and colleagues, could make it possible to store the contents of 250 DVDs in an area the size of a U.S. quarter.
COURTESY TING XU

Beyond traditional computing: At the nanoscale, quantum effects can influence electron behavior, opening the possibility for a fundamentally different form of information processing. Quantum computing is based on qubits, which, unlike binary bits, can exist in three states: 0, 1, or a third, uncertain state that influences other uncertain qubits and remains unknown until read. Using logic tailored to these qubits, quantum computers can run some calculations, especially those involving factoring large numbers, far faster than conventional computers. In the area of storage, Ting Xu (MSE) is fabricating copolymer thin films that can self assemble into a precise pattern when spread out on a surface, like soldiers lining up in perfect formation, providing super-dense storage capacity that could transform the storage industry.

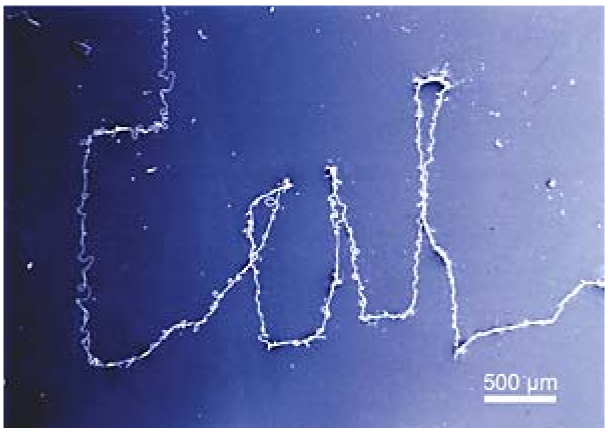
Energy and the environment

Engineering matter and energy at the nanoscale offers potential macroscale applications that could provide opportunities to generate energy more efficiently and conserve precious resources.

Thermoelectrics: One promising area is thermoelectric generators, aka Peltier devices, which, with no moving parts, convert temperature differences into electricity. Originally invented in the 19th century, these devices are inefficient because they conduct heat as well as electricity. But Arun Majumdar (ME, MSE) and colleagues are developing specialized materials with embedded nanostructures, pores or rough surfaces that block heat but not electrons—an unnatural combination of properties that could turn these generators into sources of electricity for use almost anywhere.

Solar power: Nano has already made traditional photovoltaics cheaper, and Berkeley researchers are onto even more revolutionary approaches. Paul Alivisatos (Chemistry, MSE) is developing solar cells from quantum dots of semiconductors, which can capture a wider spectrum of light than current models and convert more photon energy into electricity rather than heat. Ali Javey (EECS) and colleagues are growing highly ordered, single-crystalline nanopillar arrays of optically active semiconductors that could produce highly efficient and cost-effective photovoltaic solar cells. Connie Chang-Hasnain (EECS) has discovered nanoneedle crystals that convert single photons into cascades of electrical charge, giving them potential as both optical detectors and solar cells.

Batteries and fuel: Berkeley-based startup Seeo, founded by Mohit Singh (LBNL), is developing rechargeable lithium batteries, safer and more powerful than conventional batteries because they're filled with a nanostructured polymer electrolyte instead of a liquid. Peidong Yang (Chemistry, MSE) has found that silicon nanowires sheathed in titanium dioxide can catalyze atoms in water to split apart, using just the energy captured from sunlight, which could lead to a low-energy method for extracting hydrogen from water for use as fuel.



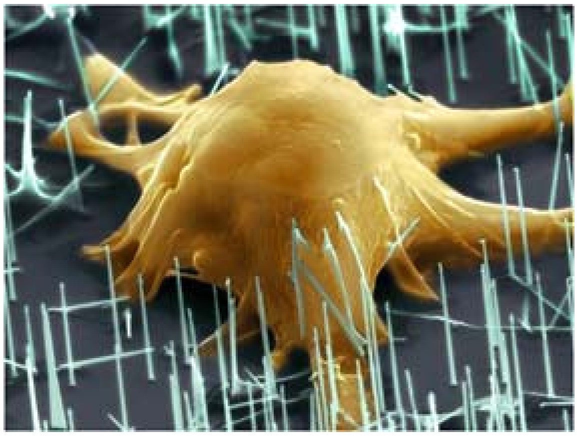
Liwei Lin and colleagues used near-field electrospinning to spell "Cal," demonstrating that nanofibers could be deposited in a controlled manner rather than the tangled mass resulting from earlier methods. The technique has potential for producing specialized wound dressings and chemical detectors.
COURTESY LIWEI LIN

Environmental monitoring: Polymer nanofibers produced using the electrospinning technique developed by Liwei Lin (ME) can be used as sensitive chemical detectors to pick up the presence of a single target molecule by how it affects the fiber's conductance. David Sedlak (CEE) has found that iron nanoparticle powder, in combination with certain catalysts, breaks down contaminants in groundwater.

Biomedical applications

Basic life processes work at the nanometer scale. Researchers are now learning to control many of these processes.

Imaging living cells: Nanoscale imaging of living processes is a major challenge. The most powerful microscopes scan with a moving probe, so specimens must be flat and inanimate (or dead) and electrically conductive or sputtered with a conductor, like gold; this works for nanotubes and microchips, but not for living cells and tissues. Xiang Zhang (ME) is working on a "superlens" made from a sheet of nano-structured material that captures photons and directs them back to a focal point. Such a lens could capture near-field scattered light, which conventional optics lose, as well as images more detailed than the half-wavelength limit of conventional optics. Luke Lee (BioE) is imaging the composition of cells by introducing a gold nanoparticle "probe" that can analyze how light scatters between it and neighboring molecules.



This scanning electron microscopic image shows a mouse embryonic stem cell cultured on an array of silicon nanowires, the work of Peidong Yang (Chemistry, MSE). The wires measure from 1 to several hundred nanometers across, the cell about 10 micrometers.
COURTESY PEIDONG YANG

Stem cells: Using the ability of stem cells to differentiate based on physical cues from the surfaces they contact, Sanjay Kumar (BioE) is using nanoengineered scaffolding to grow and study specific tissue types. Stem cells respond to physical, chemical and mechanical stimuli; Peidong Yang (Chemistry, MSE) and colleagues have demonstrated that they might also respond to electrical potentiality by using tiny nanowires to stimulate stem cells to differentiate. Seung-Wuk Lee (also BioE) pioneered a possible therapy for spinal cord repair using the M13 bacteriophage, a long, thin virus whose outer coat can be engineered to grow nanostructures. In contact with existing mature nerve cells, the modified viruses align together, forming a scaffold that stimulates progenitor nerve cells to mature into long neurons and repair the damage.

Nanofluidics: The flow of liquids and gases through nanotubes and nanopores can be finely controlled, increasing the sophistication of tiny “lab-on-a-chip” devices that can speed and reduce the cost of fluid analysis. Lydia Sohn (ME) is developing the nanocytometer, an artificial pore that measures cells one by one for conductance and attraction to antibodies, facilitating identification of cancer cells in a given sample. By applying electricity to the fluid, dissolved ions can be shuttled around, which is how Arun Majumdar (ME, MSE), Peidong Yang (Chemistry, MSE) and colleagues created the first nanofluidic transistor.

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