Little Big Science

Nanotechnology is all the rage. But will it meet its ambitious goals? And what the heck is it?

By Gary Stix

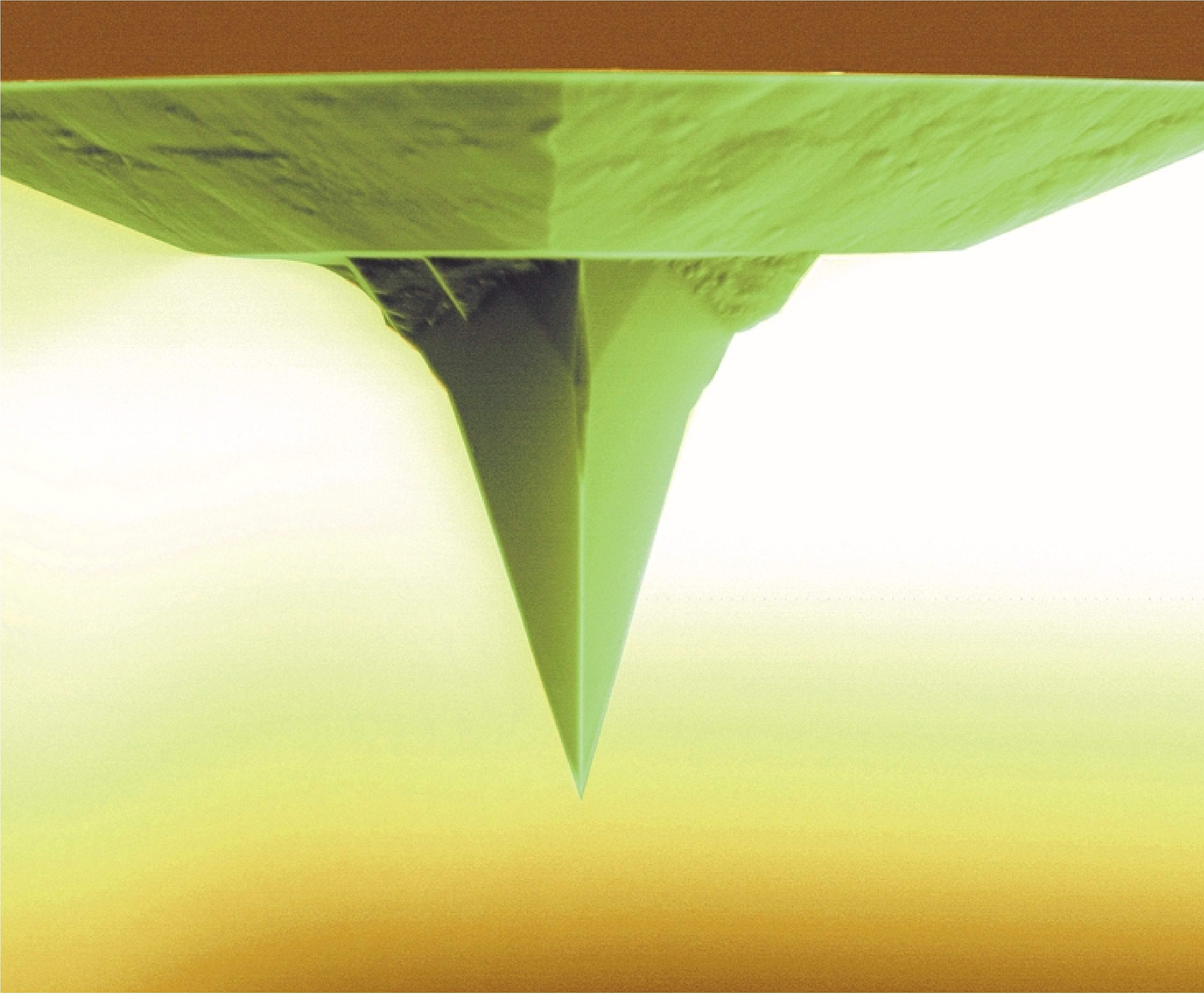
Albert Einstein, as part of his doctoral dissertation, calculated the size of a single sugar molecule from experimental data on the diffusion of sugar in water. His work showed that each molecule measures about a nanometer in diameter. At a billionth of a meter, a nanometer is the essence of small. The width of 10 hydrogen atoms laid side by side, it is one thousandth the length of a typical bacterium, one millionth the size of a pinhead, one billionth the length of Michael Jordan's well-muscled legs. One nanometer is also precisely the dimension of a big windfall for research.

Almost 100 years after Einstein's insight, the nanometer scale looms large on the research agenda. If Einstein were a graduate student today probing for a career path, a doctoral adviser would enjoin him to think small: "Nanotech, Albert, nanotech" would be the message conveyed.

After biomedical research and defense—fighting cancer and building missile shields still take precedence—nanotechnology has become the most highly energized discipline in science and technology. The field is a vast grab bag of stuff that has to do with creating tiny things that sometimes just happen to be useful. It borrows liberally from condensed-matter physics, engineering, molecular biology and large swaths of chemistry. Researchers who once called themselves materials scientists or organic chemists have transmuted into nanotechnologists.

Purist academic types might prefer to describe themselves as mesoscale engineers. But it's "nano" that generates the buzz. Probably not since Du Pont coined its corporate slogan "better things for better living through chemistry" have scientists who engage in molecular manipulation so adeptly captured and held public attention—in this case, the votes of lawmakers in Washington who hold the research purse strings. "You need to come up with new, exciting, cutting-edge, at-the-frontier things in order to convince the budget- and policy-making apparatus to give you more money," remarks Duncan Moore, a former White House official who helped to organize the Clinton administration's funding push for nanotechnology.

IMAGE BY FELICE FRANKEL, WITH TECHNICAL HELP FROM J. CHRISTOPHER LOVE



With recognition has come lots of money—lots, that is, for something that isn't a missile shield. The National Nanotechnology Initiative (NNI), announced early last year by President Bill Clinton, is a multiagency program intended to provide a big funding boost to nanoscience and engineering. The $422-million budget in the federal fiscal year that ends September 30 marks a 56 percent jump in nano spending from a year earlier. The initiative is on track to be augmented for fiscal year 2002 by another 23 percent even while the Bush administration has proposed cuts to the funding programs of most of the federal agencies that support research and development (see the NNI Web site at www.nano.gov). Nano mania flourishes everywhere. More than 30 nanotechnology research centers and interdisciplinary groups have sprouted at universities; fewer than 10 existed two years ago. Nanoism does not, moreover, confine itself to the U.S. In other countries, total funding for nanotechnology jumped from $316 million in 1997 to about $835 million this year, according to the National Science Foundation (NSF).

TIP OF ATOMIC FORCE MICROSCOPE **used to probe surfaces and manipulate molecules symbolizes the nanotechnology revolution.**

Interest in nano is also fueled, in an aberrant way, by the visions of a fringe element of futurists who muse on biblical life spans, on unlimited wealth and, conversely, on a holocaust brought about by legions of uncontrollable self-replicating robots only slightly bigger than Einstein's sugar molecules. (Check out the Web site for *NanoTechnology* magazine—http://planet-hawaii.com/nanozine/—if you want to learn about an "era of self-replicating consumer goods, super-health, super-economy and inventions impossible to fabricate with first wave industrialization.")

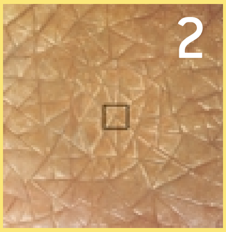
When Clinton introduced the nanotechnology initiative in a speech last year, he was long on vision and short on specifics: nanotech, he noted, might one day store the Library of Congress on a device the size of a sugar cube or produce materials with 10 times the strength of steel at a mere fraction of its

Macro, Micro, Nano

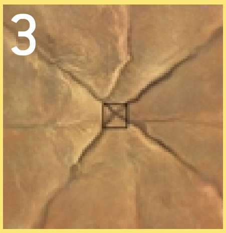
How small is a nanometer? Stepping down in size by powers of 10 takes you from the back of a hand to, at one nanometer, a view of atoms in the building blocks of DNA. The edge of each image denotes a length 10 times longer than its next smallest neighbor. The black square frames the size of the next scene inward.

Hand

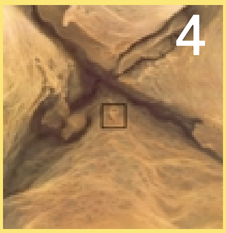
10 centimeters



1 centimeter



1 millimeter



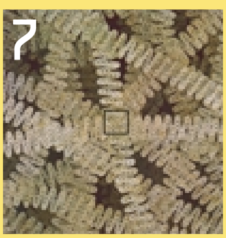
100 microns

White Blood Cell

10 microns

1 micron

DNA



100 nanometers

10 nanometers

1 nanometer

From the classic book *Powers of Ten*, by Philip and Phylis Morrison and the office of Charles and Ray Eames.

weight. But this wasn't just the meanderings of a starry-eyed politician. Surprisingly, the science establishment itself is a little unclear about what it really means when it invokes nano. "It depends on whom you ask," Stanford biophysicist Steven M. Block told a National Institutes of Health symposium on nanotechnology last year in a talk that tried to define the subject. "Some folks apparently reserve the word to mean whatever it is they do as opposed to whatever it is anyone else does."

What's in a Name?

THE DEFINITION is indeed slippery. Some of nanotechnology isn't nano, dealing instead with structures on the micron scale (millionths of a meter), 1,000 times or more larger than a nanometer. Also, nanotechnology, in many cases, isn't technology. Rather it involves basic research on structures having at least one dimension of about one to several hundred nanometers. (In that sense, Einstein was more a nanoscientist than a technologist.) To add still more confusion, some nanotechnology has been around for a while: nano-size carbon black particles (a.k.a. high-tech soot) have gone into tires for 100 years as a reinforcing additive, long before the prefix "nano" ever created a stir. For that matter, a vaccine, which often consists of one or more proteins with nanoscale dimensions, might also qualify.

But there is a *there* there in both nanoscience and nanotechnology. The nanoworld is a weird borderland between the realm of individual atoms and molecules (where quantum mechanics rules) and the macroworld (where the bulk properties of materials emerge from the collective behavior of trillions of atoms, whether that material is a steel beam or the cream filling in an Oreo). At the bottom end, in the region of one nanometer, nanoland bumps up against the basic building blocks of matter. As such, it defines the smallest natural structures and sets a hard limit to shrinkage: you just can't build things any smaller.

Nature has created nanostructures for billennia. But Mihail C. Roco, the NSF official who oversees the nanotechnology initiative, offers a more restrictive definition. The emerging field—new versus old nanotech—deals with materials and systems having these key properties: they have at least one dimension of about one to 100 nanometers, they are designed through processes that exhibit fundamental control over the physical and chemical attributes of molecular-scale structures, and they can be combined to form larger structures. The intense interest in using nanostructures stems from the idea that they may boast superior electrical, chemical, mechanical or optical properties—at least in theory. (See "Plenty of Room, Indeed," by Michael Roukes, on page 48, for a discussion of why smaller is not always better.)

Real-world nano, fitting Roco's definition, does exist. Sandwiching several nonmagnetic layers, one of which is less than a nanometer thick, between magnetic layers can produce sensors for disk drives with many times the sensitivity of previous devices, allowing more bits to be packed on the surface of each disk. Since they were first introduced in 1997, these gi-

Once conventional silicon electronics goes bust, new nanoelectronic devices are a good bet to replace them. A likely wager, though not a sure one.

ant magnetoresistive heads have served as an enabling technology for the multibillion-dollar storage industry.

New tools capable of imaging and manipulating single molecules or atoms have ushered in the new age of nano. The icons of this revolution are scanning probe microscopes—the scanning tunneling microscope and the atomic force microscope, among others—capable of creating pictures of individual atoms or moving them from place to place. The IBM Zurich Research Laboratory has even mounted the sharp, nanometer-scale tips used in atomic force microscopes onto more than 1,000 microscopic cantilevers on a microchip. The tips in the Millipede device can write digital bits on a polymer sheet. The technique could lead to a data storage device that achieves 20 times or more the density of today's best disk drives.

Varied approaches to fabricating nanostructures have emerged in the nanoworld. Like sculptors, so-called top-down practitioners chisel out or add bulk material to a surface. Microchips, which now boast circuit lines of little more than 100 nanometers, are about to become the most notable example. In contrast, bottom-up manufacturers use self-assembly processes to put together larger structures—atoms or molecules that make ordered arrangements spontaneously, given the right conditions. Nanotubes—graphite cylinders with unusual electrical properties—are a good example of self-assembled nanostructures [see "The Art of Building Small," by George M. Whitesides and J. Christopher Love, on page 38].

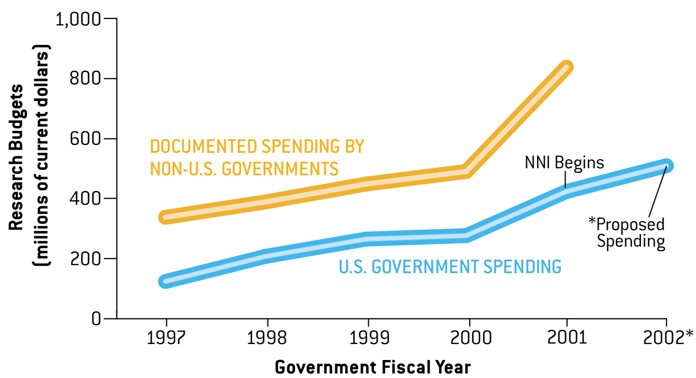
Beyond Silicon

THE DWINDLING SIZE of circuits in electronic chips drives much of the interest in nano. Computer companies with large research laboratories, such as IBM and Hewlett-Packard, have substantial nano programs. Once conventional silicon electronics goes bust—probably sometime in the next 10 to 25 years—it's a good bet that new nanotechnological electronic devices will replace them. A likely wager, though not a sure one. No one knows whether manufacturing electronics using nanotubes or some other novel material will allow the relentless improvements in chip performance without a corresponding increase in cost that characterizes silicon chipmaking [see "The Incredible Shrinking Circuit," by Charles M. Lieber, on page 58].

Even if molecular-scale transistors don't crunch zeroes and ones in the Pentium XXV, the electronics fashioned by nanotechnologists may make their way into devices that reveal the secrets of the ultimate small machine: the biological cell. Bionano, in fact, is finding real applications before the advent of postsilicon nanocomputers [see "Less Is More in Medicine," by A. Paul Alivisatos, on page 66]. Relatively few nanotags made of a semiconductor material are needed to detect cellular activity, as opposed to the billions or trillions of transistors that must all work together to function in a nanocomputer. One company, Quantum Dot Corporation, has already emerged to exploit semiconductor quantum dots as labels in biological experiments, drug-discovery research, and diagnostic tests, among other applications.

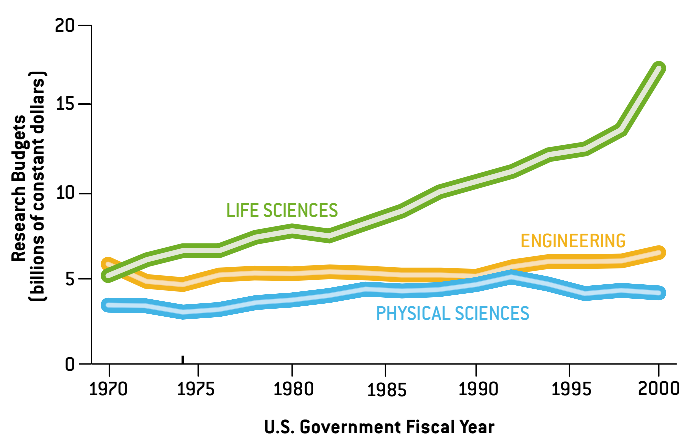
Outside biology, the earliest wave of products involves using nanoparticles for improving basic material properties. For instance, Nanophase Technologies, one of the few companies in this field that are publicly traded, produces nano-size zinc oxide particles for use in sunscreen, making the usually white-colored cream transparent because the tiny particles don't scatter visible light.

FUNDING FOR NANOTECHNOLOGY



SOURCES: U.S. Senate briefing on nanotechnology, May 24, 2001, and National Science Foundation

TRENDS IN FEDERAL RESEARCH FOR SELECTED DISCIPLINES



SOURCE: National Science Foundation

UPTICK: The National Nanotechnology Initiative (NNI), begun in fiscal year 2001, helps to keep the U.S. competitive with world spending (*top*). It also provides a monetary injection for the physical sciences and engineering, where funding has been flat by comparison with the life sciences (*bottom*).

NINA FINKEL

Nanotechnology's bid for respectability is colored by the word's association with a cabal of futurists who foresee nano as a pathway to utopia.

A Few 10^{-9} Milestones

3.5 billion years ago The first living cells emerge. Cells house nanoscale biomachines that perform such tasks as manipulating genetic material and supplying energy.
400 B.C. Democritus coins the word "atom," which means "not cleavable" in ancient Greek.
1905 Albert Einstein publishes a paper that estimates the diameter of a sugar molecule as about one nanometer.
1931 Max Knoll and Ernst Ruska develop the electron microscope, which enables subnanometer imaging.
1959 Richard Feynman gives his famed talk "There's Plenty of Room at the Bottom," on the prospects for miniaturization.
1968 Alfred Y. Cho and John Arthur of Bell Laboratories and their colleagues invent molecular-beam epitaxy, a technique that can deposit single atomic layers on a surface.
1974 Norio Taniguchi conceives the word "nanotechnology" to signify machining with tolerances of less than a micron.
1981 Gerd Binnig and Heinrich Rohrer create the scanning tunneling microscope, which can image individual atoms.
1985 Robert F. Curl, Jr., Harold W. Kroto and Richard E. Smalley discover buckminsterfullerenes, also known as buckyballs, which measure about a nanometer in diameter.
1986 K. Eric Drexler publishes *Engines of Creation,* a futuristic book that popularizes nanotechnology.
1989 Donald M. Eigler of IBM writes the letters of his company's name using individual xenon atoms.
1991 Sumio Iijima of NEC in Tsukuba, Japan, discovers carbon nanotubes.
1993 Warren Robinett of the University of North Carolina and R. Stanley Williams of the University of California at Los Angeles devise a virtual-reality system connected to a scanning tunneling microscope that lets the user see and touch atoms.
1998 Cees Dekker's group at the Delft University of Technology in the Netherlands creates a transistor from a carbon nanotube.
1999 James M. Tour, now at Rice University, and Mark A. Reed of Yale University demonstrate that single molecules can act as molecular switches.
2000 The Clinton administration announces the National Nanotechnology Initiative, which provides a big boost in funding and gives the field greater visibility.
2000 Eigler and other researchers devise a quantum mirage. Placing a magnetic atom at one focus of an elliptical ring of atoms creates a mirage of the same atom at another focus, a possible means of transmitting information without wires.

The government's nanotech initiative goes beyond sunscreen. It envisages that nanostructured materials may help reduce the size, weight and power requirements of spacecraft, create green manufacturing processes that minimize the generation of unwanted by-products, and form the basis of molecularly engineered biodegradable pesticides. The field has such a broad scope—and basic research is still so new in some nanosubspecialties—that worries have arisen about its ability to deliver on ambitious technology goals that may take 20 years to achieve. "While nanotechnology may hold great promise, some scientists contend that the field's definition is too vague and that much of its 'hype' may not match the reality of present scientific speculation," noted a Congressional Research Service report last year.

Nanodreams

ANY ADVANCED RESEARCH carries inherent risks. But nanotechnology bears a special burden. The field's bid for respectability is colored by the association of the word with a cabal of futurists who foresee nano as a pathway to a techno-utopia: unparalleled prosperity, pollution-free industry, even something resembling eternal life.

In 1986—five years after IBM researchers Gerd Binnig and Heinrich Rohrer invented the scanning tunneling microscope, which garnered them the Nobel Prize—the book *Engines of Creation,* by K. Eric Drexler, created a sensation for its depiction of godlike control over matter. The book describes self-replicating nanomachines that could produce virtually any material good, while reversing global warming, curing disease and dramatically extending life spans. Scientists with tenured faculty positions and NSF grants ridiculed these visions, noting that their fundamental improbability made them an absurd projection of what the future holds.

But the visionary scent that has surrounded nanotechnology ever since may provide some unforeseen benefits. To many nonscientists, Drexler's projections for nanotechnology straddled the border between science and fiction in a compelling way. Talk of cell-repair machines that would eliminate aging as we know it and of home food-growing machines that could produce victuals without killing anything helped to create a fascination with the small that genuine scientists, consciously or not, would later use to draw attention to their work on more mundane but eminently more real projects. Certainly labeling a research proposal "nanotechnology" has a more alluring ring than calling it "applied mesoscale materials science."

Less directly, Drexler's work may actually draw people into science. His imaginings have inspired a rich vein of science-fiction literature [see "Shamans of Small," by Graham P.

Collins, on page 86]. As a subgenre of science fiction—rather than a literal prediction of the future—books about Drexlerian nanotechnology may serve the same function as *Star Trek* does in stimulating a teenager's interest in space, a passion that sometimes leads to a career in aeronautics or astrophysics.

The danger comes when intelligent people take Drexler's predictions at face value. Drexlerian nanotechnology drew renewed publicity last year when a morose Bill Joy, the chief scientist of Sun Microsystems, worried in the magazine *Wired* about the implications of nanorobots that could multiply uncontrollably. A spreading mass of self-replicating robots—what Drexler has labeled "gray goo"—could pose enough of a threat to society, he mused, that we should consider stopping development of nanotechnology. But that suggestion diverts attention from the real nano goo: chemical and biological weapons.

Among real chemists and materials scientists who have now become nanotechnologists, Drexler's predictions have assumed a certain quaintness; science is nowhere near to being able to produce nanoscopic machines that can help revive frozen brains from suspended animation. (Essays by Drexler and his critics, including Nobel Prize winner Richard E. Smalley, appear in this issue.) Zyvex, a company started by a software magnate enticed by Drexlerian nanotechnology, has recognized how difficult it will be to create robots at the nanometer scale; the company is now dabbling with much larger micromechanical elements, which Drexler has disparaged in his books [see "Nanobot Construction Crews," by Steven Ashley, on page 84].

Even beyond meditations on gray goo, the nanotech field struggles for cohesion. Some of the research would have proceeded regardless of its label. Fusing "nano" and "technology" was an after-the-fact designation: IBM would have forged ahead in building giant magnetoresistive heads whether or not the research it was doing was labeled nanotechnology.

For the field to establish itself as a grand unifier of the applied sciences, it must demonstrate the usefulness of grouping widely disparate endeavors. Can scientists and engineers doing research on nanopowders for sunscreens share a common set of interests with those working on DNA computing? In some cases, these crossover dreams may be justified. A semiconductor quantum dot originally developed for electronics and now being deployed to detect biological activity in cells is a compelling proof of principle for these types of transdisciplinary endeavors.

If the nano concept holds together, it could, in fact, lay the groundwork for a new industrial revolution. But to succeed, it will need to discard not only fluff about nanorobots that bring cadavers back from a deep freeze but also the overheated rhetoric that can derail any big new funding effort. Most important, the basic nanoscience must be forthcoming to identify worthwhile nanotechnologies to pursue. Distinguishing between what's real and what's not in nano throughout this period of extended exploration will remain no small task. SA

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Nano for Sale

Not all nanotechnology lies 20 years hence, as the following sampling of already commercialized applications indicates.

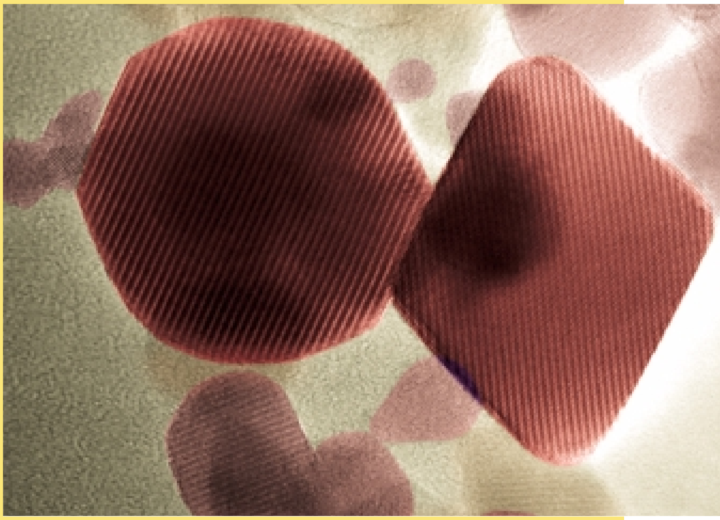
APPLICATION: CATALYSTS
COMPANY: EXXONMOBIL
DESCRIPTION: Zeolites, minerals with pore sizes of less than one nanometer, serve as more efficient catalysts to break down, or crack, large hydrocarbon molecules to form gasoline.

APPLICATION: DATA STORAGE
COMPANY: IBM
DESCRIPTION: In the past few years, disk drives have added nanoscale layering—which exploits the giant magnetoresistive effect—to attain highly dense data storage.

APPLICATION: DRUG DELIVERY
COMPANY: GILEAD SCIENCES
DESCRIPTION: Lipid spheres, called liposomes, which measure about 100 nanometers in diameter, encase an anticancer drug to treat the AIDS-related Kaposi's sarcoma.

APPLICATION: MANUFACTURE OF RAW MATERIALS
COMPANY: CARBON NANOTECHNOLOGIES
DESCRIPTION: Co-founded by buckyball discoverer Richard E. Smalley, the company has made carbon nanotubes more affordable by exploiting a new manufacturing process.

APPLICATION: MATERIALS ENHANCEMENT
COMPANY: NANOPHASE TECHNOLOGIES
DESCRIPTION: Nanocrystalline particles are incorporated into other materials to produce tougher ceramics, transparent sunblocks to block infrared and ultraviolet radiation, and catalysts for environmental uses, among other applications.



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