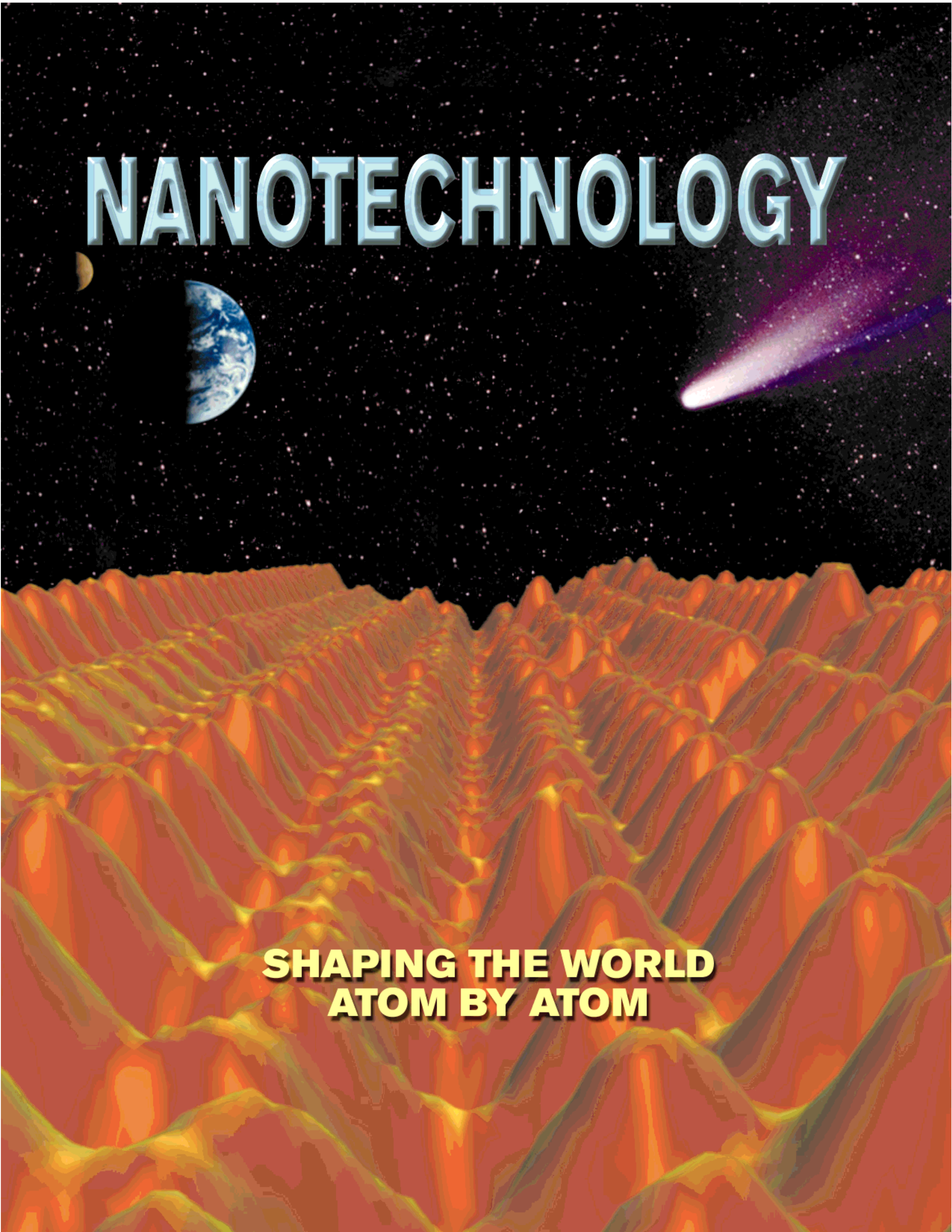
NANOTECHNOLOGY



SHAPING THE WORLD ATOM BY ATOM

National Science and Technology Council
Committee on Technology
The Interagency Working Group on Nanoscience, Engineering and Technology
September 1999

About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space and technology policies across the Federal Government. NSTC acts as a "virtual" agency for science and technology (S&T) to coordinate the diverse parts of the Federal research and development (R&D) enterprise. The NSTC is chaired by the President. Membership consists of the Vice President, Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant S&T responsibilities, and other White House officials.

An important objective of the NSTC is the establishment of clear national goals for Federal S&T investments in areas ranging from information technologies and health research, to improving transportation systems and strengthening fundamental research. The Council prepares R&D strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NSTC, contact 202-456-6100 or see the NSTC web site: http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/NSTC_Home.html

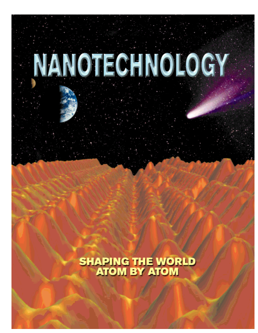
Interagency Working Group on Nanoscience, Engineering and Technology (IWGN)

Chair: M.C. Roco, NSF.
White House IWGN Co-chair: T.A. Kalil, Special Assistant to the President, WH Economic Council.
Vice-chair: R. Trew, DOD.
Executive Secretary: J.S. Murday, NRL.
Members: K. Kirkpatrick (OSTP); J. Porter (NSTC); D. Radzanowski (OMB);
P. Genther-Yoshida (DOC/TA); M.P. Casassa, R.D. Shull (DOC/NIST); G.S. Pomrenke (DOD/AFOSR);
I.L. Thomas, R. Price, B.G. Volintine (DOE); R.R. John, A. Lacombe (DOT/Volpe Center);
E. Murphy (DoTREAS); S. Venneri, G.H. Mucklow, M. Meyyappan, G. Krabach (NASA); J.A. Schloss,
E. Kousvelari (NIH); T.A. Weber, M.P. Henkart (NSF).
Public Affairs Consultant: J. Canton.

Acknowledgements:

Ivan Amato, Writer
Liz Carroll, Design/Layout
Geoff Holdridge, Coordinator, WTEC Director, Loyola College

This report was prepared under the guidance of NSTC/CT. Any opinions, conclusions or recommendations expressed in this material are those of the authors, and do not necessarily reflect the views of the U.S. Government or individual funding agencies.



L. J. Whitman/Naval Research Laboratory

On the cover:
This combination of a scanning tunneling microscope image of a silicon crystal's atomic surfacescape with cosmic imagery evokes the vastness of nanoscience's potential.

Nanotechnology: Shaping The World Atom By Atom

The emerging fields of nanoscience and nanoengineering are leading to unprecedented understanding and control over the fundamental building blocks of all physical things. This is likely to change the way almost everything—from vaccines to computers to automobile tires to objects not yet imagined—is designed and made.

If you were to deconstruct a human body into its most basic ingredients, you'd get a little tank each of oxygen, hydrogen, and nitrogen. There would be piddling piles of carbon, calcium, and salt. You'd squint at pinches of sulfur, phosphorus, iron, and magnesium, and tiny dots of 20 or so other chemical elements. Total street value: not much.

With its own version of what scientists call nanoengineering, nature transforms these inexpensive, abundant, and inanimate ingredients into self-generating, self-perpetuating, self-repairing, self-aware creatures that walk, wiggle, swim, sniff, see, think, and even dream. Total value: immeasurable.

Now, a human brand of nanoengineering is emerging. The field's driving question is this: What could we humans do if we could assemble the basic ingredients of the material world with even a glint of nature's virtuosity? What if we could build things the way nature does—atom by atom and molecule by molecule?

Scientists already are finding answers to these questions. The more they learn, the more they suspect nanoscience and nanoengineering will become as socially transforming as the development of running water, electricity, antibiotics, and microelectronics. The field is roughly where the basic science and technology behind transistors was in the late 1940s and 1950s.

In April 1998, Neal Lane, Assistant to the President for Science and Technology and former Director of the National Science Foundation (NSF), stated at a Congressional hearing, "If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

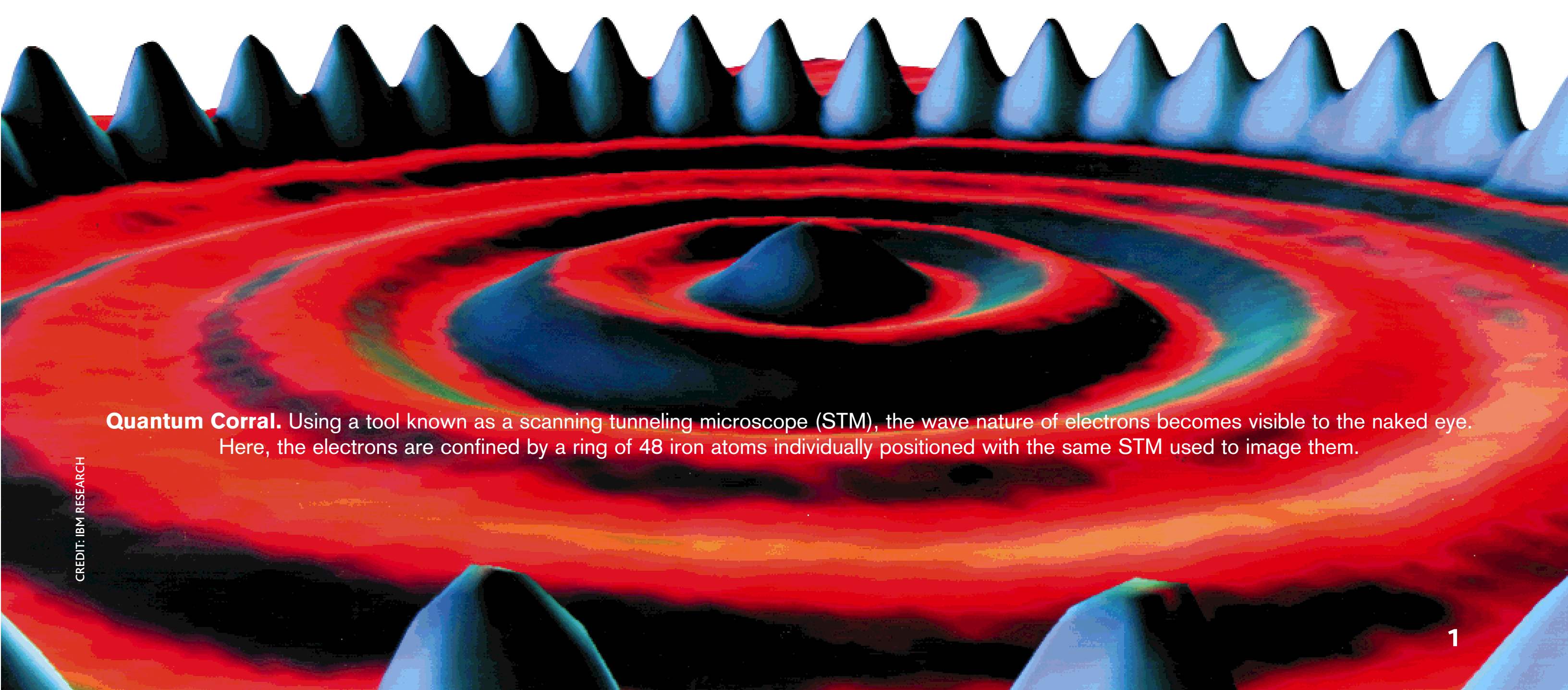
Lane is not alone in this view. Many scientists, including physicist and Nobel laureate Horst Stormer of Lucent Technologies and Columbia University, are themselves amazed that the emerging nanotechnology may provide humanity with unprecedented control over the material world. Says Stormer: "Nanotechnology has given us the tools...to play with the ultimate toy box of nature—atoms and molecules. Everything is made from it...The possibilities to create new things appear limitless."

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

–Neal Lane
Assistant to the President For Science and Technology

So what do scientists like Lane and Stormer mean by nanotechnology? In the language of science, the prefix nano means one-billionth of something like a second or a meter (see sidebar, p. 3). Nanoscience and nanotechnology generally refer to the world as it works on the nanometer scale, say, from one nanometer to several hundred nanometers. That's the natural spatial context for molecules and their interactions, just as a 100 yard gridiron is the relevant spatial context for football games. Naturally-occurring molecular players on the nanoscale field range from tiny three-atom water molecules to much larger protein molecules like oxygen-carrying hemoglobin with thousands of atoms to gigantic DNA molecules with millions of atoms. Whenever scientists and engineers push their understanding and control over matter to finer scales, as they now are doing on the nanoscale, they invariably discover qualitatively new phenomena and invent qualitatively new technologies. "Nanotechnology is the builder's final frontier," remarks Nobel laureate Richard Smalley, Rice University.

For years now, scientists have been developing synthetic nanostructures that



Quantum Corral. Using a tool known as a scanning tunneling microscope (STM), the wave nature of electrons becomes visible to the naked eye. Here, the electrons are confined by a ring of 48 iron atoms individually positioned with the same STM used to image them.

CREDIT: IBM RESEARCH

could become the basis for countless improved and completely new technologies. The way molecules of various shapes and surface features organize into patterns on nanoscales determines important material properties, including electrical conductivity, optical properties, and mechanical strength. So by controlling how that nanoscale patterning unfolds, researchers are learning to design new materials with new sets of properties.

Some of these nanostructures may turn out to be useful as discrete nanostructures. New types of vaccines and medicines come to mind here. The value of others may emerge only as they are assembled into larger structures like particles or fibers, which then would be processed into yet larger structures like textiles, films, coatings, bricks, and beams.

Forward looking researchers believe they could end up with synthetic creations with life-like behaviors. Cover an airplane with paint containing nanoscale pigment particles that instantly reconfigure, chameleon-like, to mimic the aircraft's surroundings. You would end up with an airplane indistinguishable from the sky, that is, an invisible plane. How about bricks and other building materials that can sense weather conditions and then respond by altering their inner structures to be more or less permeable to air and humidity? That would go a long way toward improving the comfort and energy efficiency of buildings. And how about synthetic antibody-like nanoscale drugs or devices that might seek out and destroy malignant cells wherever they might be in the body?

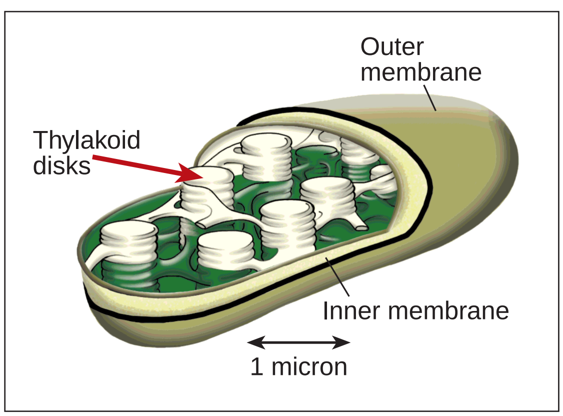
For many years futurists steeped in the culture of science fiction and prone to thinking in time frames that reach decades ahead have been dreaming up a fantastic future built using nanotechnologies. More recently, more cautious, established researchers, who are developing the tools and methods for a nanotechnological future, have been making projections of their own based on their expanding base of knowledge and experience. "As we enter the 21st century, nanotechnology will have a major impact on the health, wealth and security of the world's people that will be at least as significant in this century as antibiotics, the integrated circuit, and man-made polymers," according to a committee of leading scientists that convened in January 1999 at the National Science Foundation to assess the potential roles of nanotechnology in the coming years.

Not that it will be easy. Nanoscience and nanoengineering remain in an exploratory phase. Scientists have yet to understand all of the scientific and engineering issues that define what can happen and what can be done in the nanoscale regime. Still, laboratory accomplishments so far are making scientists in this country and elsewhere bullish about the future. So much so that the quest to master the nanoscale is becoming a global competition. New lightweight materials for future generations of more fuel efficient cars, military aircraft that can go farther and carry more payload, new classes of pharmaceuticals, materials that last longer and thereby reduce pollution from manufacturing, are just a few of the goals. Companies and countries are experimenting with new organizational, industrial and budgetary models they hope will give them the competitive edge toward these ends.

"Nanotechnology has given us the tools...to play with the ultimate toy box of nature—atoms and molecules. Everything is made from it...The possibilities to create new things appear limitless."

– Horst Stormer
Lucent Technologies and Columbia University,
Physics Nobel Prize Winner

The U.S. Government, for one, invested approximately $116 million in fiscal year 1997 in nanotechnology research and development. For FY 1999, that figure has risen to an estimated $260 million. Japan and Europe are making similar investments. Whoever becomes most knowledgeable and skilled on these nanoscopic scales probably will find themselves well positioned in the ever more technologically-based and globalized economy of the 21st century.



Natural nanotechnology: Much of the photosynthesis that powers forests unfolds inside tiny cellular power houses called chloroplasts (above). These contain nanoscale molecular machinery (including pigment molecules like chlorophyll) arranged inside stacked structures, called thylakoid disks, that convert light and carbon dioxide into biochemical energy.

ILLUSTRATION: LIZ CARROLL, ADAPTED FROM NANOGEN

That helps explain why the White House National Science and Technology Council (NSTC) created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in 1998. With members from eight Federal agencies interacting closely with the academic and industrial community, the IWGN's charge has been to assess the potential of nanotechnology and to formulate a national research and development plan. The Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) have since issued a joint memorandum to Federal agency heads that recommends nanotechnology as a research priority area for Federal investment in FY 2001. The memorandum calls for a broad-based coalition in which academe, the private sector, and local, state, and Federal governments work together to push the envelope of nanoscience and nanoengineering to reap nanotechnology's potential social and economic benefits. The working group has recommended a doubling of the annual investment for research in these areas to about a half billion dollars.

Some Deep Roots for a Nanotechnological Future

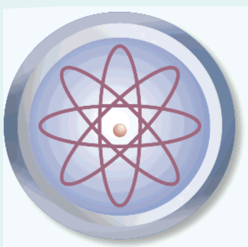
Nanotechnology is a new word, but it's not an entirely new field. Chemical catalysis, which underlies a significant portion of the country's gross national product, is an example of "old nanotechnology." Today, catalysts speed up thousands of chemical transformations like those that convert crude oil into gasoline, small organic chemicals into life-saving drugs and polymers, and cheap graphite into synthetic diamond for making industrial cutting tools. They're akin to biological catalysts—the enzymes in cells that orchestrate the chemistry of life. Most catalysts were discovered by trial and error—by "shaking and baking" metals and ceramics and then seeing how the result affects the reactions and their products. On closer examination with modern tools, many of these catalysts turn out to be highly organized metallic and/or ceramic nanostructures whose specific architectures trigger changes in molecules that temporarily dock to them. Researchers expect this nanoscale understanding of catalysis to lead

The Incredible Tininess of Nano

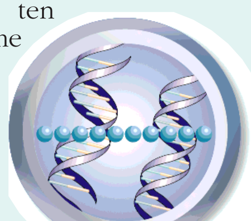
"Nano" derives from the Greek word for dwarf. Use it as a prefix for any unit like a second or a liter and it means a billionth of that unit. A nanosecond is one billionth of a second. A nanoliter is one billionth of a liter. And a nanometer is one billionth of a meter—about the length of a few atoms lined up shoulder to shoulder. The bottom of this letter, "l", spans about one million nanometers.

A world of things is built up from the tiny scale of nanometers. Just consider the thousands of cellular proteins and enzymes that do everything from metabolizing hamburgers, to building up muscle fibers, to replicating DNA, whose twisty structure itself is a few nanometers thick. Enzymes typically are constructions of thousands of atoms in precise molecular structures that span some tens of nanometers. That kind of natural nanotechnology is about ten times smaller than some of the smallest synthetic nanotechnology humanity has made so far. The individual components of an Intel Pentium III microprocessor span about 200 nanometers. That's why these chips can harbor several million transistors and can translate a five-inch Digital Video Disc (DVD) into a seamless movie. Nanotechnology researchers say today's microelectronics are mere hints of what will come from engineering that begins on the even smaller scales of nanostructures. In the summer of 1999, researchers reported making single molecules that behave like transistors. Talk of computers the size of sugar cubes suddenly became less speculative.

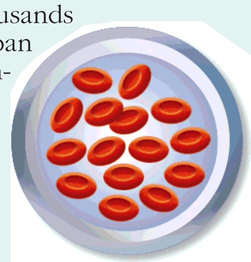
Just as the prefix "micro" has infiltrated the general lexicon ever since early microscopists began observing the world on finer scales, the prefix "nano" has begun diffusing into popular culture. It's getting into screenplays and scripts for TV shows like the X-files and Star Trek: The Next Generation. Companies are using it in their names. It's a favorite topic of science fiction writers. And it's on the agenda of corporate executives, deans, and government officials deciding how to allocate funds and resources among the many research and development projects vying for support.



Less than a nanometer
Individual atoms are up to a few angstroms, or up to a few tenths of a nanometer, in diameter.



Nanometer
Ten shoulder-to-shoulder hydrogen atoms (blue balls) span 1 nanometer. DNA molecules are about 2.5 nanometers wide.



Thousands of nanometers
Biological cells, like these red blood cells, have diameters in the range of thousands of nanometers.

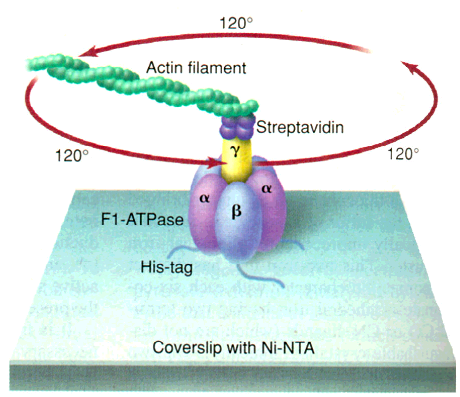
A million nanometers
The pinhead sized patch of this thumb (circled in black) is a million nanometers across.

Billions of nanometers
A two meter tall male is two billion nanometers tall.

to better, cleaner, and more capable industrial processes.

Even an early instance of nanotechnology like catalysis really is young compared to nature's own nanotechnology, which emerged billions of years ago when molecules began organizing into the complex structures that could support life. Photosynthesis, biology's way of harvesting the solar energy that runs so much of the planet's living kingdom, is one of those ancient products of evolution. Scientists often perceive photosynthesis as the result of brilliantly engineered molecular ensembles—which include light-harvesting molecules such as chlorophyll—arranged within cells on the nanometer and micrometer scales. These ensembles capture light energy and convert it into the chemical energy (which is stored in chemical bonds) that drives the biochemical machinery of plant cells.

The abalone, a mollusk, serves up another perennial favorite in nature's gallery of enviable nanotechnologies. These squishy creatures construct super-tough shells with beautiful, iridescent inner surfaces. They do this by organizing the same calcium carbonate of crumbly schoolroom chalk into tough nanostructured bricks. For mortar, abalones concoct a stretchy goo of protein and carbohydrate. Cracks that may start on the outside rarely make it all the way through; the structure of the shell forces a crack to take a tortuous route around the tiny bricks, which dissipates the energy behind the damage. Adding to the damage control is that stretchy mortar. As a crack grows, the mortar forms resilient nanostrings that try to force any separating bricks back together. The result is a Lilliputian masonry that can withstand sharp beaks, teeth, even hammer blows.



Cellular Nanotech. Nanoscale machines enable cells to carry out basic functions. The F1-ATPase complex, depicted in a diagram above, enables cells to produce the biochemical fuel it needs.

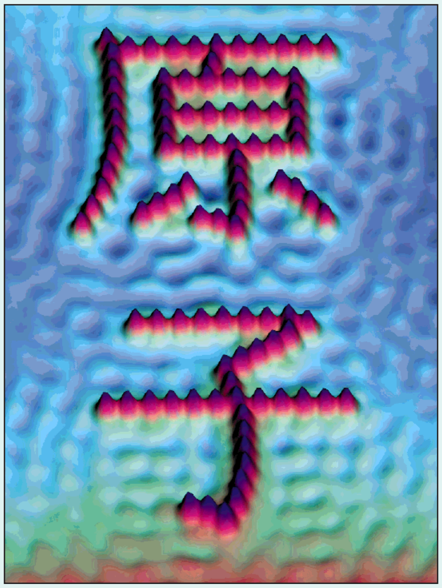
This clever engineering of the abalone shell reflects one of nanotechnology's most enticing faces: by creating nanometer-scale structures, it's possible to control the fundamental properties—like color, electrical conductivity, melting temperature, hardness, crack-resistance, and strength—of materials without changing the materials' chemical composition. The stuff of soft chalk becomes hard shell.

Another feat of natural nanotechnology is in continuous operation every time you take a breath, move a muscle, live another second. Known antiseptically as F1-ATPase complexes, they're actually

Surely You're Joking Mr. Feynman: The Original Nanotechnology Vision

One of the first to articulate a future rife with nanotechnology was Richard Feynman, a drum-playing, jester-spirited, irreverent Nobel laureate who died in 1988. In late 1959 at the California Institute of Technology, he presented what has become one of 20th century science's classic lectures. Titled "There is Plenty of Room at the Bottom," it also has become part of the nanotechnology community's founding liturgy.

Feynman was wowed by biology. "A biological system can be exceedingly small," he reminded his audience. "Many of the cells are very tiny, but they are active; they manufacture substances; they walk around; they wiggle; and they do all kind of marvelous things–all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want—that we can manufacture an object that maneuvers at that level!"



Writing With Atoms. Written literally with atoms, the Japanese Kanji above—each just a few nanometers across—means "atom."

He was talking about nanotechnology before the word existed. Feynman regaled his audience with a technological vision of extreme miniaturization in 1959, several years before the word "chip" became part of the lexicon. Extrapolating from known physical laws, Feynman argued it was possible (with, say, an electron beam that could form lines in materials) to write all 25,000 pages of the 1959 edition of the Encyclopedia Britannica in an area the size of a pin head! He calculated that a million such pinheads would amount to an area of about a 35 page pamphlet. Said Feynman: "All of the information which all of mankind has ever recorded in books can be carried in a pamphlet in your hand–and not written in code, but a simple reproduction of the original pictures, engravings and everything else on a small scale without loss of resolution."

And that's just how his talk began. He outlined how, with proper coding, all the world's books at the time actually could be stored in something the size of a dust speck, with each of the million billion bits in those books requiring a mere 100 atoms to store. How about building computers using wires, transistors, and other components that were that small? "They could make judgements," Feynman predicted. He spoke about using big tools to make smaller tools suitable for making yet smaller tools, and so on, until researchers had tools sized just right for directly manipulating atoms and molecules.

"And what might that mean?," asked Feynman. Chemistry would become a matter of literally placing atoms one by one in exactly the arrangement you want. "Up to now," he added, "we have been content to dig in the ground to find minerals. We heat them and we do things on a large scale with them, and we hope to get a pure substance with just so much impurity, and so on. But we must always accept some atomic arrangement that nature gives us...I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do."

Repeatedly, during this famous lecture, Feynman reminded his audience that he wasn't joking. "I am not inventing anti-gravity, which is possible someday only if the laws are not what we think," he said. "I am telling you what could be done if the laws are what we think; we are not doing it simply because we haven't yet gotten around to it."

molecular motors inside cells. Each of these motors is a complex of proteins bound to the membranes of mitochondria, the cell's bacteria-sized batteries. About 10 nanometers across, the F1-ATPase complexes are key players in the synthesis of ATP—the molecular fuel for cellular activity. Scientists have found that F1-ATPase complexes also generate rotary motion just like fan motors whirring in summertime windows. By attaching tiny protein filaments to the hub of F1-ATPase, researchers have visualized this rotary action. And it sets their own nanoengineering imaginations into motion with designs for human-made nanometer-scale machines.

Scientists using tools like electron microscopes to look at natural structures like abalone shells and protein complexes hope to emulate some of biology's nanoscale engineering. Their aim is to create structural materials for stronger, lighter, more damage-resistant and otherwise better man-made constructions ranging from buildings and cars to batteries and prosthetic limbs.

From chalk to abalone shell . . . this is the "alchemy" of natural nanotechnology without human intervention. And now physicists, chemists, materials scientists, biologists, mechanical and electrical engineers, and many other specialists are pooling their collective knowledge and tools so that they too can tailor the world on atomic and molecular scales. Abilities like this in the coming century could make the accomplishments of the 20th century seem quaint.

Even forty years ago, the physicist Richard Feynman envisioned a coming era of nanoscience and technology. In a famous 1959 lecture titled, "There's Plenty of Room at the Bottom," he outlined what were then far-out possibilities. They don't seem quite so far-out anymore (see sidebar above).

"Nanotechnology is the way of ingeniously controlling the building of small and large structures, with intricate properties; it is the way of the future, a way of precise, controlled building, with incidentally, environmental benignness built in by design."

– Roald Hoffmann
Cornell University,
Chemistry Nobel Prize Winner

What's so Special About Nano

Nanotechnology stands out as a likely launch pad to a new technological era because it focuses on perhaps the final engineering scales people have yet to master.

CREDIT: IBM RESEARCH

The pyramids in Egypt, the Brooklyn Bridge, and automobiles are conspicuous monuments to how well and how long people have controlled matter on large scales of meters and miles. The products of Swiss watchmakers even several centuries ago proved that human control over the material world had extended downward a thousandfold to the millimeter scale or so. Over the past few decades, researchers have pushed this control down another hundredfold. Using microlithographic techniques, they've learned to inscribe silicon with ultra-dense patterns of circuitry whose individual components now are only visible with powerful electron microscopes.

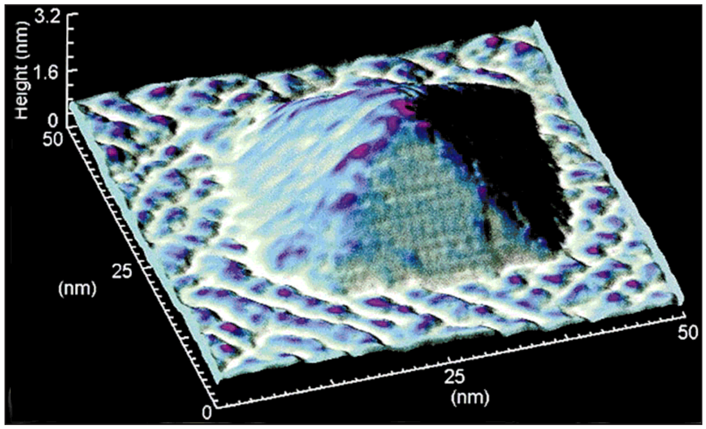
And all the while, chemists have been learning to mix, blend, heat, react, and otherwise process chemicals to produce millions of different specific molecular structures. This is about the finest level of material structure relevant for making things. In so doing, researchers have developed recipes and protocols for making the plastics, ceramics, semiconductors, metals, glass, fabrics, composites and other materials of the constructed landscape.

But there's a big gap between the scale of individual molecular structures made by chemists and the the sub-microscopic components on microprocessors made by electrical engineers. That gap, which spans from about one nanometer to several hundred nanometers, is where fundamental properties are defined.

So with every advance researchers make in nanotechnology, they stitch together an unbroken engineering nexus from atoms on up to skyscrapers. Roald Hoffmann, a chemist and Nobel Prize laureate at Cornell University has put it this way: "Nanotechnology is the way of ingeniously controlling the building of small and large structures, with intricate properties; it is the way of the future, a way of precise, controlled building, with incidentally, environmental benignness built in by design."

Going Quantum. Many researchers expect that better control over the way atoms and molecules assemble into tiny structures could lead to a host of new technologies based on quantum phenomena that become prevalent only at nanometer scales.

In the normal-sized realm of books, bricks, cars and houses, quantum mechanics—the conceptual framework scientists use to describe and predict the properties of matter on the levels of atoms and electrons—doesn't have much direct relevance. As long as bricks hold up the house, who cares about their quantum specifics? But now researchers actually are creating nanoscale building blocks, such as metallic and ceramic particles, and all-carbon "nanotubes," that are hundreds of millions of times smaller than bricks used for houses and tubes used for plumbing. So scientists are finding themselves in the middle of quantum mechanics territory.



Modern Pyramids. This nanoscale pyramid of germanium atoms—one kind of quantum dot—formed spontaneously atop a ground of silicon. It could help researchers develop new generations of tinier electronic devices that are governed by quantum phenomena.

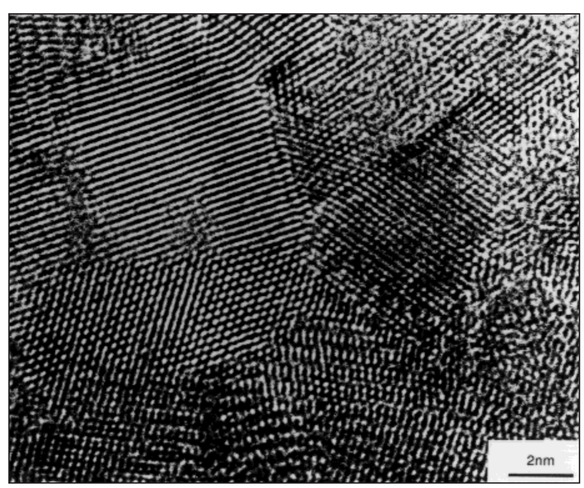
In this nanoscale territory, electrons, for one, no longer flow through electrical conductors like rivers. On this scale, an electron's quantum mechanical nature expresses itself as a wave. This behavior makes it possible for electrons to do remarkable things, such as instantly tunnel through an insulating layer that normally would have stopped it dead. The payoff of this behavior is that electronic devices built on nanoscales not only can pack more densely on a chip but also can operate far faster—and with dramatically fewer electrons and less energy loss—than conventional transistors.

These characteristics ultimately could yield more powerful computers that can help scientists mimic phenomena better and engineers design products better. In some specially designed materials with nanoscale layers made of different semiconductor materials, electrons exhibit behaviors not possible in less precisely organized settings. Researchers already have exploited this quantum mechanical reality to design and build new solid state lasers that emit light in wavelengths good for tasks like monitoring pollution, tracking chemical reactions, and optical communications.

What's more, researchers already have taken steps toward so-called quantum computers based on the energy states of atoms and electrons. Theorists predict that quantum computers, if they can be realized, will be able to calculate millions, even billions, of times faster than today's supercomputers. Nanotechnology may propel early laboratory steps and theoretical projections like these toward practical versions.

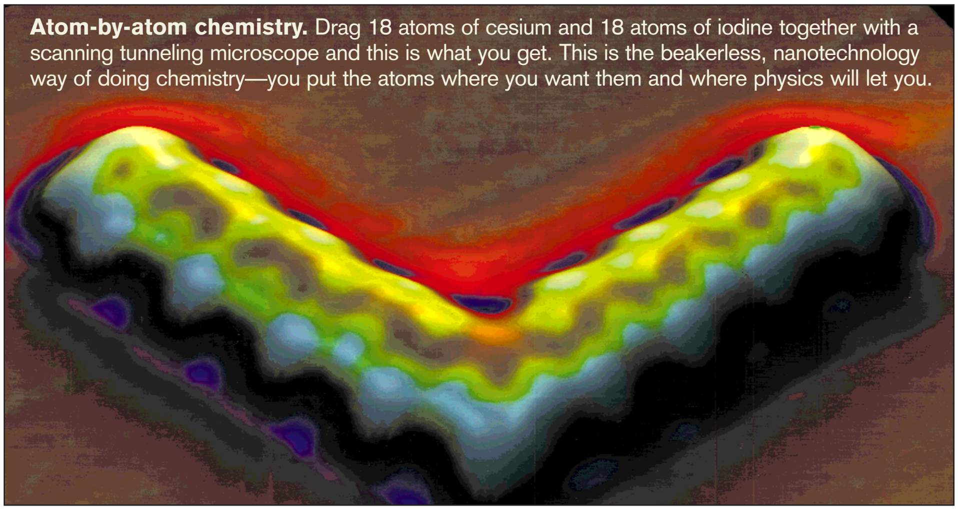
Surfaces Galore. Another major fountain of new technology is likely to spout from a simple fact of material reality: as objects become smaller, the proportion of their constituent atoms at or near the surface rises. Collections of very small particles, therefore, have high surface area compared to their volume. This characteristic is profound because so much of what happens in the world happens at surfaces. Photosynthesis occurs on surfaces inside of cells. Catalysis happens on the surfaces of particles. Ice in the atmosphere forms on the surfaces of floating dust specks.

Smaller industrial catalysts, or ones with labyrinthine interiors with nanoscale features, mean there's more surface area for thousands of chemical transformations. Make a ceramic brick or a metal part, such as a jet engine's turbine blade, out of nanoscale powder particles instead of conventional microscale powder particles and the amount of internal surface goes up dramatically. There's no chemical difference between the two materials; only the size of their constituent particles differs. Yet, just for that the nanostructured brick or metal piece may be harder, less likely to crack, or



Nanograins. Each region of parallel lines reveals a nanoscale grain of palladium metal. Here, a dozen or so such particles are joined into a nanostructured metal. It has dramatically smaller grains with more internal boundaries than metals made from more conventional grains, and that leads to a stronger metal.

CREDITS: (TOP TO BOTTOM) HEWLETT-PACKARD; RICHARD SIEGEL



Atom-by-atom chemistry. Drag 18 atoms of cesium and 18 atoms of iodine together with a scanning tunneling microscope and this is what you get. This is the beakerless, nanotechnology way of doing chemistry—you put the atoms where you want them and where physics will let you.

stronger at higher temperatures, than the conventional brick. That's important for people who make things like armor or turbine blades for jet engines, which run more efficiently the hotter they become. The shift to nanoscale building blocks for making metal, ceramic, polymer and other material components is enabling researchers to "dial-in" many properties—like melting temperature, magnetic properties (e.g., the magnetic detection ability of materials in the read heads of hard disks), and color—that previously were impossible to obtain for a particular material.

Forty Years of Getting Around to It

Since Richard Feynman's prescient lecture 40 years ago about the opportunities harbored in small scale engineering, thousands of scientists have been developing the knowledge and means to intervene on the nanoscale. Now, human beings routinely see and manipulate individual atoms and molecules in their laboratories.

The tools and methods for making and testing these diminutive objects have arcane names like scanning tunneling microscopes, molecular beam epitaxy, and molecular self-assembly. Scientists also rely heavily on extremely powerful computers to model and simulate nanoscale structures and phenomena. That helps them use their theories better and to make sense of what they see through their microscopes. Simulation and modeling also help them evaluate the infinite number of possible nanostructures they could in principle try to build. Simulations can help steer researchers toward fruitful directions and away from dead ends. After all, on the nanoscale one misplaced atom could make or break a quantum computer.

Here's a sampling of some of the new tools available:

• **Seeing Atoms.** One of the biggest steps toward nanoscale control was in 1981 when researchers at IBM's Research Center in Switzerland—led by Gerd Binning and Heinrich Rohrer—told the world about their scanning tunneling microscope, or STM. It's essentially a superfine stylus that sweeps over a surface like a blind person's walking stick. But since the stylus is just a few atom-widths away and it has a molecularly or perhaps atomically fine tip, something quantum mechanical happens. Electrons "tunnel" across the gap between the surface and the tip as the tip scans over the surface.

This technique enables a computer to construct fantastically enlarged images of atomic or molecular landscapes normally impossible to see. The STM's inventors received a Nobel Prize because their invention quickly enabled thousands of researchers finally to "see" the atomic and molecular landscapes of things.

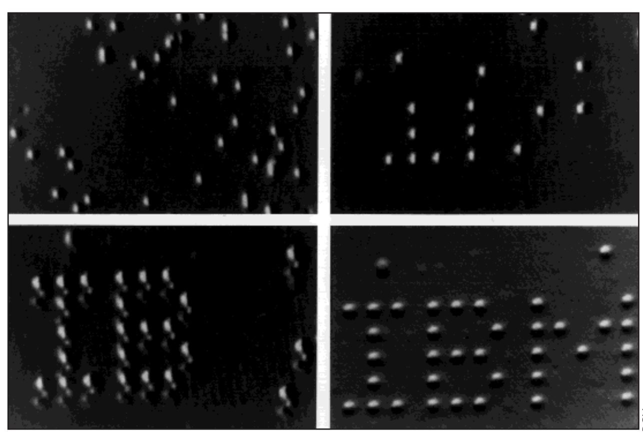
So taken with the new view of the nanoworld STMs offered, scientists have developed a raft of related instruments now known collectively as scanning probe microscopes (SPMs). Now, besides STM images of surface structures, scientists use SPMs like scanning tunneling spectroscopes and near field scanning optical microscopes to analyze the identities of molecules and atoms on surfaces. They use scanning thermal microscopes to see how heat travels on and through nanostructures such as solid-state lasers, made like a cake with tens or hundreds of nanoscale layers of different semiconductor materials. They use scanning force microscopy to examine magnetic domains on storage media like hard disks.

• **Moving Atoms.** SPMs can do more than just peek in on previously hidden nanoscale environments. Donald Eigler of IBM's Almaden Research Center remembers the day in 1990 when he and Erhard K. Schweizer, who was visiting from the Fritz-Haber Institute in Berlin, moved individual atoms for the first time. In his laboratory notebook Eigler used big letters and an exclamation mark to write THIS IS FUN! Using one of the most precise measuring and manipulating tools the world had ever seen, the researchers slowly finessed 35 xenon atoms to spell out the three letter IBM logo atop a crystal of nickel. To be sure, it only worked in a vacuum chamber kept at temperatures that make the North Pole seem tropical. But it was the kind of sub-microscopic manipulation that Feynman was talking about. The entire logo spanned under three nanometers.

Since that feat, more researchers have used STMs to create letters, pictures, as well as exotic physical structures on surfaces one atom at a time. And some researchers now are developing atom- and molecule-moving tools that are easier to use.

Consider a nanomanipulator that is being developed by a collaboration based at the University of North Carolina, Chapel Hill. With it, people can manipulate nanostructures in real time using what amounts to a sophisticated joy stick that controls a scanning tunneling microscope. The developers of the system built it with force-feedback so operators even "get a feel" for the atoms and molecules they are moving. What's more, the link between the joystick and the actual nanomanipulator is electronically mediated, which means it even can be controlled via the Internet. Students in a nearby North Carolina high school used this nanomanipulator across the Internet to see, feel and modify individual virus particles.

These invaluable tools have opened many new doors of discovery. But using a single tip of a scanning probe microscope either for imaging or manipulating surfaces or tiny particles is painfully slow. In the past few years, SPM developers have been

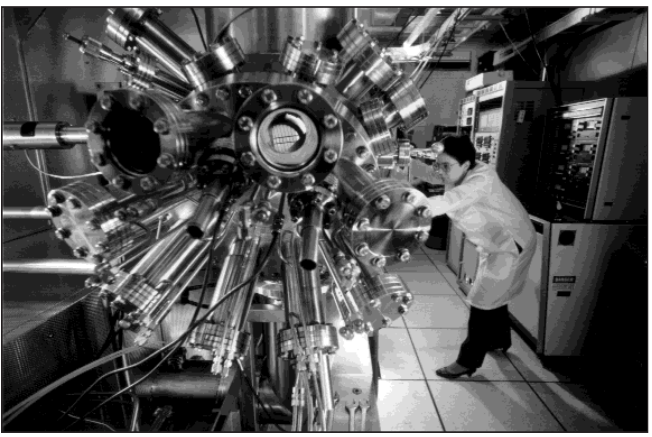


Smallest Writing. This famous set of images, now about 10 years old, helped prove to the world that people indeed can move atoms. The series shows how 35 atoms were moved to form a famous logo.

CREDITS: IBM RESEARCH

hooking up many SPM tips in arrangements that work in parallel. The difference is akin to building a house all by yourself versus getting a dozen friends to help.

• **Spray Painting with Atoms.** Scanning probe microscopes are not the only game in town for nanomanipulation. Another favorite tool is known as molecular beam epitaxy, or MBE. With it, researchers can create specialized crystals one atomic or molecular layer at a time. It's like spray painting with atoms. From little ovens charged with basic ingredients, atoms or molecules effuse into a chamber where they then deposit onto a heated surface placed inside. Computer-controlled shutters control which ingredients enter the chamber at any particular time. The result is a tool for building layered materials—like the laser-emitting semiconductors that read your CDs—atomic layer by atomic layer.



Metallic Medusa. Machines like this molecular beam epitaxy instrument can grow materials even one atomic layer at a time.

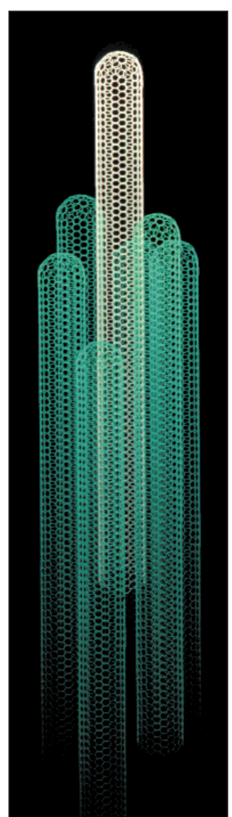
Researchers use MBE and other related tools that deposit thin films of material to make so-called giant magnetoresistance (GMR) materials. In this class of materials, electrical resistance changes drastically in the presence of a magnetic field. They're in the read/write heads in computers' hard drives. As the head rides over a magnetic domain (a bit, that is), its resistance will reflect the domain's magnetic state, which corresponds to the one or zero of the digital world. By growing crystals with alternating nanoscale layers of materials like magnetic iron and nonmagnetic chromium, researchers about 10 years ago found they could create materials with GMR. They're far more sensitive, which means disk makers can pack magnetic domains more closely and read data faster. GMR-based read heads are the key components for the market in hard drives that amounted to $34 billion dollars in 1998.

Researchers also are developing new memory chips using GMR materials that preserve the data even in the absence of electricity. They say GMR-based nonvolatile magnetic random access memory (MRAM) chips that can store 100 megabits might be available in just a few years. A few years after that, three-dimensional versions of MRAMs with capacities up to about 10 billion bits (gigabits) could be ready. That could make hard drives, and their relatively slow data access rates, high power consumption, and bulk, a has-been technology.

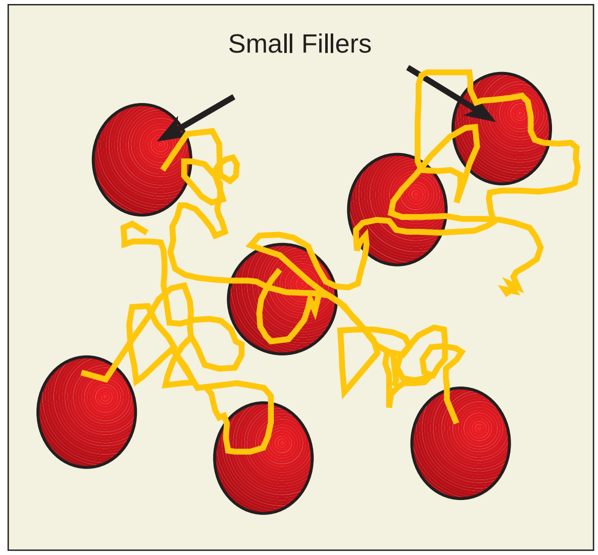
• **Molecular Self-Assembly.** SPMs and MBE machines are only examples of a large and growing number of tools for observing the world on the nanoscale and for building structures from atomic and molecular scratch. Nanotechnology researchers love their newfound ability to move atoms on surfaces, but they also want to be able to manipulate and assemble nanoscale particles into supramolecular constructions and even larger structures.

In the past decade or so, chemists—such as Nobel laureate Jean-Marie Lehn, University of Strasbourg—have been developing a set of techniques known as molecular self-assembly. The idea is to design molecular building blocks that automatically snap together in predesignated ways. And researchers believe they can use this technique as a new route to making everything from circuitry elements to new polymers that manipulate light in optical communications systems.

There already are plenty of examples showing how scientists are learning the rules of molecular self-assembly. For example, researchers have exploited self-assembly techniques to create a "wire" consisting of a single, electrically conductive molecule that connects the ends of two much larger gold leads. In another related case, researchers have created the molecular equivalent of transistors using minuscule nanotubes made of carbon atoms that self-assemble (under the right conditions) into cylinders a mere 1.2 nanometers in diameter, or about one ten-thousandth the diameter of a human hair. To do this, the researchers used an atomic force microscope (a relative of the scanning tunneling microscope) to position a nanotube between two metal leads. There, the nanotube behaves like the on-off gate of a much larger, conventional transistor.



Nanotubes. All-carbon nanotubes (here with diameters of 1.2 nanometers) are promising for applications ranging from new structural materials that are stronger and lighter weight to electronic components for new supercomputers to drug delivery systems.



Perpetual Plastics? By adorning the polymer structure of synthetic plastic with ceramic nanoparticles, researchers hope to develop new substances that will last far longer.

There is a long way to go before anything like "molecular electronics"—and the sugar-cube sized computers they could make happen—becomes possible. But laboratory feats like these suggest such visions are more than mere fantasy.

In a related assembly process, researchers use specialized detergent molecules that organize into honeycomb-like structures. These structures then serve as templates for the formation of more permanent structures made out of ceramic or polymer materials for such uses as catalysts and medical implants.

Some of the early glimpses of what these and other assembly processes will yield already are of the head-shaking kind. Researchers that once only had dreamed of making molecular-scale versions of the transistors, wires, and other microelectronic components on chips, are actually making such things. Scientists at Hewlett-Packard, for one, have made wires less than a dozen atoms thick. What's more, they and researchers at UCLA, Yale University, and elsewhere have been making tangible progress toward molecular logic gates that could function somewhat like the relatively

CREDITS: (TOP TO BOTTOM) RENSSELAER POLYTECHNIC INSTITUTE; BELL LABS/LUCENT; RICE UNIVERSITY gargantuan transistors on microelectronic chips. "In two to five years, you will begin to see functioning circuits which are of recognizable utility," one molecular electronics researcher told the New York Times.

Nanotechnologists Project That Their Work Will Leave No Stone Unturned

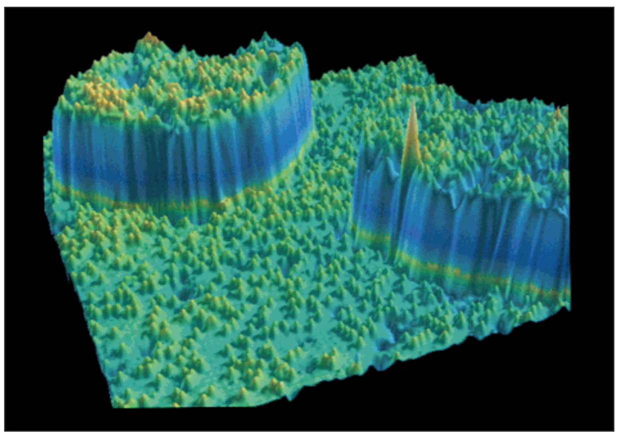
The list of nanotechnologies in various stages of conception, development and even commercialization already is vast and growing. If present trends in nanoscience and nanotechnology continue, most aspects of everyday life are subject to change. Consider these:

• **Electronics Central.** By patterning recording media in nanoscale layers and dots, the information on a thousand CDs could be packed into the space of a wristwatch. Besides the thousandfold to millionfold increase in storage capacity, computer processing speeds will make today's Pentium IIIs seem slow. Devices to transmit electromagnetic signals—including radio and laser signals—will shrink in size while becoming inexpensive and more powerful. Everyone and everything conceivably could be linked all the time and everywhere to a future World Wide Web that feels more like an all-encompassing information environment than just a computer network.

• **Nanodoc.** Nanotechnology will lead to new generations of prosthetic and medical implants whose surfaces are molecularly designed to interact with the body. Some of these even will help attract and assemble raw materials in bodily fluids to regenerate bone, skin or other missing or damaged tissues. New nanostructured vaccines could eliminate hazards of conventional vaccine development and use, which rely on viruses and bacteria. Nanotubules that act like tiny straws could conceivably take up drug molecules and release them slowly over time. A slew of chip-sized home diagnostic devices with nanoscale detection and processing components could fundamentally alter patient-doctor relationships, the management of illnesses, and medical culture in general.

• **Smokeless Industry.** More and more materials and products will be made from the bottom-up, that is, by building them up from atoms, molecules, and the nanoscale powders, fibers and other small structural components made from them. This differs from all previous manufacturing, in which raw materials like sheet metal, polymer, fabric and concrete get pressed, cut, molded and otherwise coerced into parts and products. Bottom-up manufacturing should require less material and pollute less. What's more, engineers expect to be able to embed sophisticated, life-like functions into materials. Even concrete will get smart enough to internally detect signs of weakness and life-like enough to respond by, say, releasing chemicals that combat corrosive conditions. In effect, the constructed world itself could become sensitive to damaging conditions and automatically take corrective or evasive action like a hand recoiling from a flame.

• **Planes, Trains and Automobiles.** Materials with an unprecedented combination of strength, toughness and lightness will make all kinds of land, sea, air and space vehicles lighter and more fuel efficient. Fighter aircraft designed with lighter and stronger nanostructured materials will be able to fly longer missions and carry more payload. Plastics that wear less because their molecular chains are trapped by ceramic nanoparticles will lead to materials that last a lifetime. Some long-view researchers are taking steps toward self-repairing metallic alloys that automatically fill in and reinforce tiny cracks that can grow and merge into larger ones, including catastrophic ones that have caused plane crashes.



Memorable Clues. The raised mesas in this scanning tunneling microscope image are made of iron atoms. This atomic landscape forms when chromium deposits onto an iron surface. Nanoscale data like this could lead to new recording media.

• **But, Wait, There's More!** Nanotechnology advocates say their field will leave no stone unturned. Their lengthy lists include artificial photosynthesis systems for clean energy; molecular layer-by-layer crystal growth to make new generations of more efficient solar cells; tiny robotic systems for space exploration; selective membranes that can fish out specific toxic or valuable particles from industrial waste or that can inexpensively desalinate sea water; chameleon-like camouflage that changes shape and color to blend in anywhere, anytime; and blood substitutes.

Ready or Not

No one knows how much of nanotechnology's promise will prove out. Technology prediction has never been too reliable. In the March 1949 edition of Popular Mechanics, hardly a year after the invention of the transistor, experts predicted computers of the future would add as many as 5000 numbers per second, weigh only 3000 pounds, and consume only 10 kilowatts of power. Today's five-pound laptops add several million numbers per second using only a watt or so of power. And thumbnail-sized microprocessors run washing machines and kids' toys as well as hundreds of millions of computers. What's more, computer technology spawned a new social epoch that some dub the Information Age or the Silicon Age.

And yet, many believe nanotechnology may do even more. In the collective opinion of the committee of scientists, engineers and technology professionals convened in January 1999 by the IWGN, "The total societal impact of nanotechnology is expected to be much greater than that of the silicon integrated circuit because it is applicable in many more fields than just electronics."

Despite the advances researchers have made, it is hard to work on the nanoscale. And even assuming something like Feynman's vision of total nanoscale control comes about, the consequences are bound to be mixed. Like any extremely powerful new technology, nanotechnology will bring with it social and ethical issues.

Just consider quantum computers. Theorists expect them to be so good at factoring huge numbers that the toughest encryption schemes in use today—which are enabling revolutionary things like e-commerce—will become easy to crack. Or consider the claim that nanobiology will enable people to live longer, healthier lives. Longer average lifetimes will mean more people on Earth. But how many more people can the Earth sustain?

For the moment, it's nanotechnology's promise that's on most peoples' minds. "Never has such a comprehensive technology promised to change so much so fast... Inevitably nanotech will give people more time, more value for less cost and provide for a higher quality of existence," predicts James Canton, president of the Institute for Global Futures. But maybe not for everyone. Says Canton: "Those nations, governments, organizations and citizens who are unaware of this impending power shift must be informed and enabled so that they may adequately adapt."

It no longer seems a question of whether nanotechnology will become a reality. The big questions are how important and transformative nanotechnology will become, will it become affordable, who will be the leaders, and how can it be used to make the world a better place?—questions that will, in time, be answered.

CREDIT: NIST

The following documents have been prepared by the Interagency Working Group on Nanoscience, Engineering, and Technology (IWGN):

• National Nanotechnology Initiative, internal NSTC/CT/IWGN report, reviewed by the President's Committee of Advisors on Science and Technology (PCAST) Nanotechnology Panel. Expected release in February 2000 (see http://www.nsf.gov/nano/).

• Nanostructure Science and Technology (NSTC report). R.W. Siegel, E. Hu, and M.C. Roco, eds. 1999. Worldwide study on status and trends; available on the Web: http://itri.loyola.edu/nano/IWGN.Worldwide.Study/, on CD-ROM from WTEC, and as hard-cover publication from Kluwer Academic Publishers (1999).

• Nanotechnology Research Directions: IWGN Workshop Report. M.C. Roco, R.S. Williams, and P. Alivisatos, eds. 1999. Provides input from the academic, private sector and government communities; available on the Web: http://itri.loyola.edu/nano/IWGN.Research.Directions/.

• Nanotechnology – Shaping the World Atom by Atom (NSTC report). I. Amato. 1999. Brochure for the public (this report); available on the Web: http://itri.loyola.edu/nano/IWGN.Public.Brochure/.

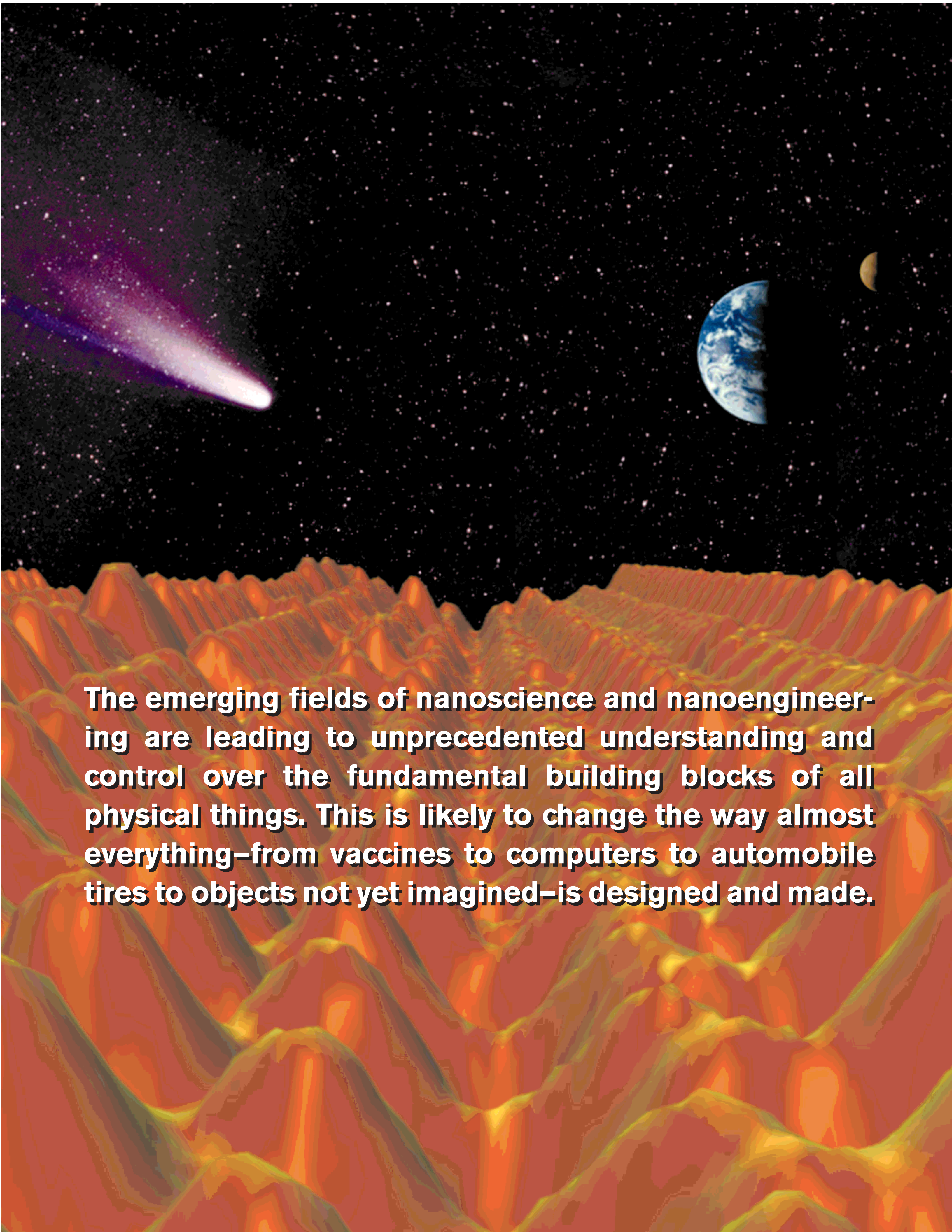
Additional information on U.S. activities in nanotechnology can be found in the following report:

• R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States (includes review of U.S. funding), sponsored by 7 agencies in 1997, Proceedings published in January 1998, R.W. Siegel, E. Hu and M.C. Roco, eds., WTEC, on the Web: http://itri.loyola.edu/nano/US.Review/.

Additional information on the National Nanotechology Initiative will be posted on the Web:

• OSTP Committee on Technology Homepage at http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/committee/ct.html

• National Science Foundation Homepage at http://www.nsf.gov/nano/



The emerging fields of nanoscience and nanoengineering are leading to unprecedented understanding and control over the fundamental building blocks of all physical things. This is likely to change the way almost everything–from vaccines to computers to automobile tires to objects not yet imagined–is designed and made.