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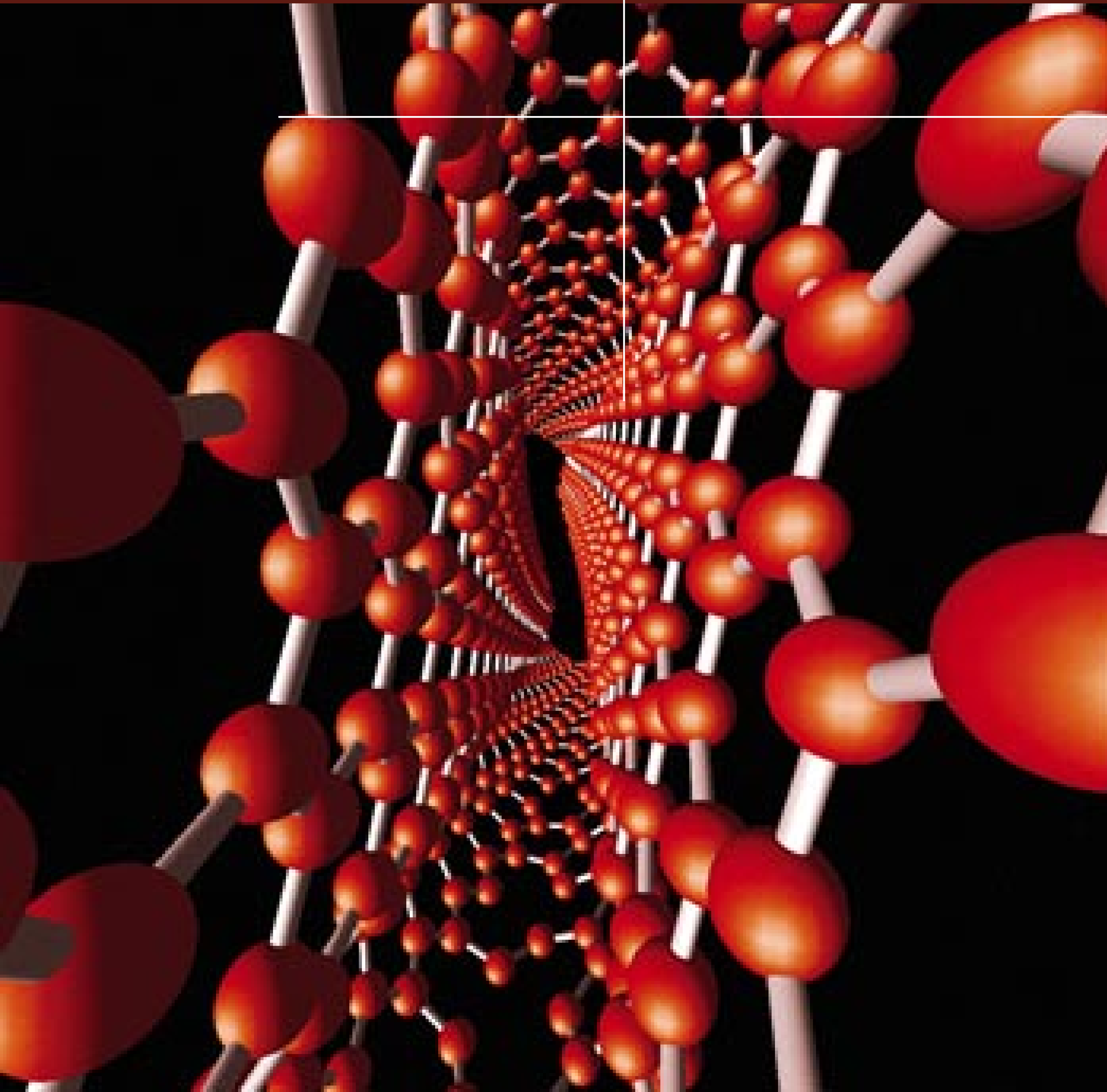
BAY AREA SCIENCE AND INNOVATION CONSORTIUM

Nanotechnology in the San Francisco Bay Area:

Dawn of a New Age



Nanotechnology in the San Francisco Bay Area:
Dawn of a New Age

This report was produced by the Bay Area Science and Innovation Consortium (BASIC), an action-oriented collaboration of the region's major research universities, national laboratories, independent research institutions, and research and development-driven businesses and organizations.

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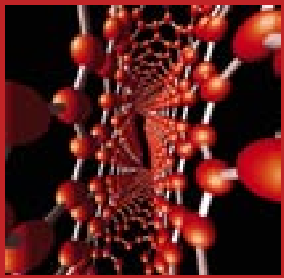
Advancing the Bay Area's Leadership in Science, Technology, and Innovation



Cover:

The next big thing in technology is going to be very very small. Nanotechnology offers the promise of manufacturing materials and products at the atomic and molecular levels, as shown by this depiction of a carbon nanotube. Economists are predicting a trillion dollar global market for nanoproducts within the next ten years. (image courtesy of Berkeley Lab)

Message from the Chairman

Since the early 20th Century, collaborative scientific research and technological developments have played key roles in fueling the Bay Area's intellectual and economic vitality. From the invention of the cyclotron to the creation of Silicon Valley's microelectronics revolution and the biotech industry, the fertile confluence here of inventors, scientists and entrepreneurs has helped make this area one of the world's most vibrant and successful regions.

The Bay Area Science and Innovation Consortium (BASIC) was created to stimulate and facilitate productive collaborations and to alert Bay Area officials and residents to the future benefits that healthy R&D efforts bring to this region.

One way we have chosen to do this is by preparing a series of reports that highlight the local achievements and prospects in newly evolving areas of scientific research that have the potential to stimulate new waves of scientific and commercial success in the Bay Area.

This is the first in the BASIC-sponsored series of "Science Futures" reports. In it, we examine the exciting arena called nanotechnology.

Nanotechnology itself doesn't stem from a single invention. Rather, relentless progress in physics, chemistry and biology research have led to the same space -- the realm of individual atoms and molecules which are measured in nanometers, or billionths of a meter. Our premier research universities and national labs -- as well as many start-up companies and international corporations -- have been deeply active in nanoscience and nanotechnology for more than 10 years. With new facilities and tools planned for the near future, we can continue to claim leadership in this important scientific area.

One needn't be a scientist to appreciate both the wonder and the reality of the opportunities presented by working at the nanoscale. From human health to efficient manufacturing, the prospects are tremendous. The practical benefits of researchers working for or partnering with companies that will provide nanotechnology products plays to our strength as a region.

BASIC is proud of the nanotechnology accomplishments of its members and the many other innovators in the Bay Area. We support their ongoing efforts to improve our economy and our quality of life.

Dr. Robert J. T. Morris
Chairman

“The only way of discovering the limits of the possible is to venture a little way past them into the impossible.”

— Arthur C. Clarke’s Second Law of Technological Development

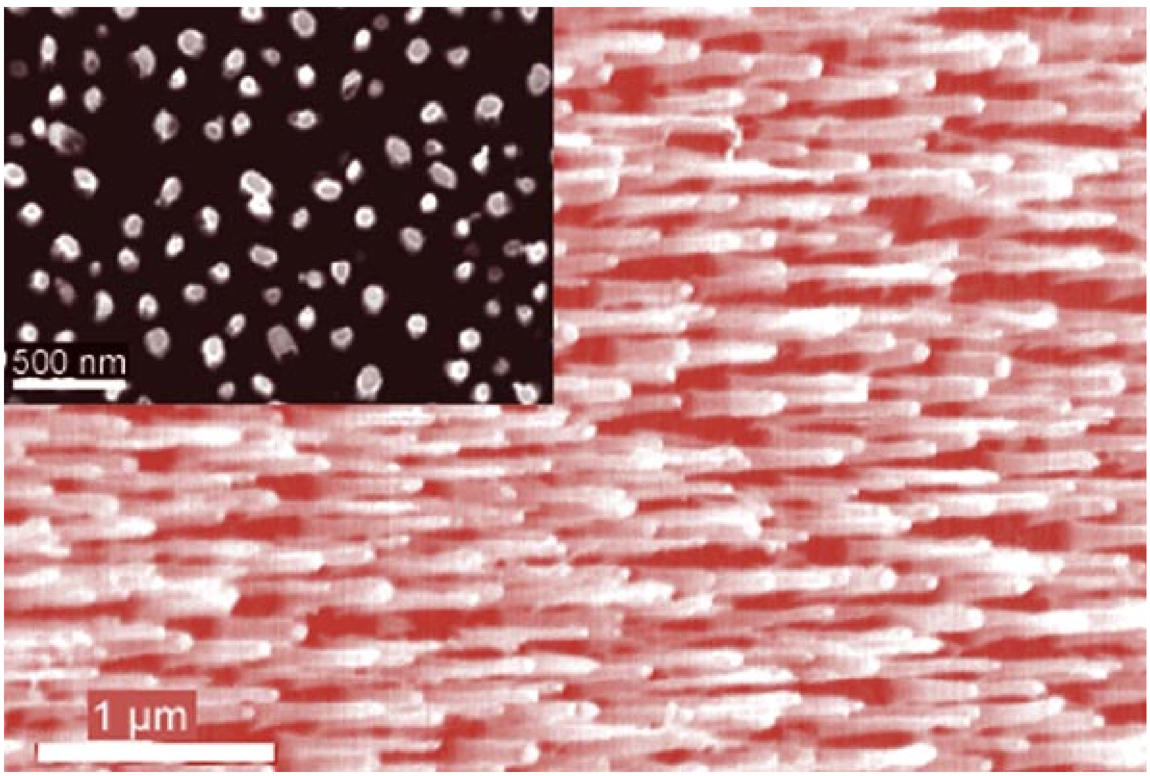
Executive Summary

No longer the stuff of science fiction, nanotechnology has arrived and is here to stay. Economists with the National Science Foundation predict a trillion dollar global market for nanoproducts by the year 2015. The federal government is already investing billions of dollars in nanoresearch. Northern California's San Francisco Bay Area, which served as the research and development cradle of microtechnology, is advantageously positioned to lead the evolution into nanotechnology.

Member organizations of BASIC – the Bay Area Science and Innovation Consortium – which include national laboratories, research universities, and some of the country's leading R&D laboratories in private industry, have already launched strong nanoscience programs across a broad spectrum of disciplines. Springing up also are a new crop of state-of-the art research centers, such as the Molecular Foundry, the Bio-Nanotechnology Center and the Nanogeoscience Center in Berkeley, the NASA Ames Center for Nanotechnology, and Stanford's Nanofabrication Facility in Silicon Valley.

Even as these fledgling research efforts are being grown and developed, they have yielded dividends in terms of actual devices and significant technological advances. For example, BASIC member scientists were the first to position individual atoms. They've also created a laser too small to be seen by the most powerful optical microscope, a computer memory bit so tiny that more than 1,000 could fit on the end of a single strand of human hair, a biosensor that can collect and identify airborne particles of anthrax in a split second, and a carbon chip designed to restore vision to patients going blind from macular degeneration.

These and many more examples are presented in this report, which is intended to explain what nanotechnology is, why it has so much promise in so many different areas, what are the challenges for realizing that promise, and what has been accomplished to date by the men and women in the research and development community of the San Francisco Bay Area.



This image from NASA-Ames shows an American flag made from carbon nanotubes using a plasma carbon vapor deposition technique. The stripes are side views of the tubes which measure one micron in length. The "stars" against the blue field are the nanotubes viewed from the top.

The earth has given us 92 natural elements, the fundamental substances we process into all the materials we use. We have an especially bountiful supply of the ones we use most. Each year we harvest about 15 billion tons of ores that we process into metals; chemicals that we process into fuels, polymers and ceramics; animal and plant products that we process into food and fiber, and so on.

The vast array of different materials we fabricate from the elemental goods the earth provides is staggering in its diversity and breadth of function. However, our principle methods of processing — melting, chilling, vaporizing, pounding, cutting, drilling, casting, forging, etc. — use up finite resources and energy and heavily contribute to pollution. This has resulted in global problems that have become increasingly acute with the passage of time.

What all of today's most widely used processing techniques have in common is that they take place on a macroscopic scale, that is, they all involve the handling of billions upon billions of atoms of any given element at a time. Consider the possibilities if the materials we fashion could instead be assembled with atomic precision. This is not unprecedented; nature has been doing it for millions of years with biological molecules. Our processing methods could become more energy-efficient and less polluting. The persistent energy shortages and environmental damage that plague human civilization today might be substantially reduced. That is the remarkable promise of nanotechnology and a big reason why out of all the research and development areas that are considered "hot" today, there is none hotter.

Anticipating the profound impact that nanotechnology will have on the national economy, the U.S. federal government has embarked upon an ambitious multimillion dollar National Nanotechnology Initiative (NNI). More than $800 million in federal funds have been appropriated for research under the initiative this year. In December 2003, President Bush signed the 21st Century Nanotechnology Research and Development Act, which authorizes $3.7 billion for nanotechnology R&D to be carried out over the next four years by the National Science Foundation (NSF), U.S. Department of Energy (DOE), National Institute of Standards and Technology, National Aeronautics and Space Administration and the Environmental Protection Agency. The legislation's bipartisan sponsors were U.S. Representatives Mike Honda (Dem., Calif.) and Sherwood Boehlert (Rep., N.Y.) and Senators Joe Lieberman (Dem., Conn.), Ron Wyden (Dem., Ore.) and George Allen (Rep.,Va).

"The nanotechnology industry could become one of the new engines of our economy," said

Congressman Honda. "It is important that the United States lead the world in the development of the nanotechnology industry, and it will take many years of sustained federal investment in research and development to achieve this goal."

Added Congressman Boehlert, chairman of the House Science Committee, "I've come to understand that in science and technology, few things could actually be bigger than nanotechnology in terms of its potential to revolutionize scientific and engineering research, improve human health and bolster our economy."

The U.S is not alone in its pursuit of nanotechnology. At least 30 other countries – led by Japan, Germany and Switzerland – have also initiated national nanotechnology R&D activities. This political enthusiasm is fueled by the reports of economic experts, such as those with the NSF, who predict a trillion dollar global impact for nanotechnology products by 2015.

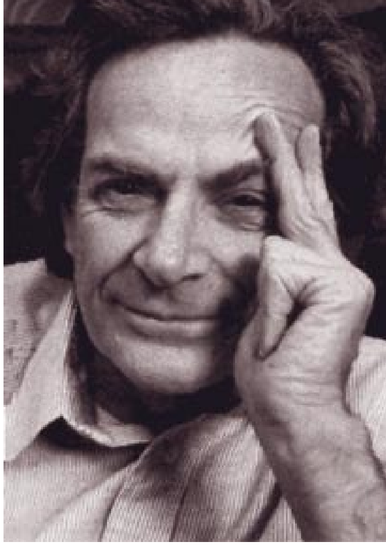
Research centers dedicated to the exploration and development of nanotechnology have already been established throughout the nation at key public and private laboratories and universities. Programs in the materials, chemical, and biological sciences which focus on critical nanotechnology questions have begun to make significant advances. It should come as no surprise that many of these research centers and successful programs are located in the San Francisco Bay Area. Having served as the research and development cradle of the microtechnology age, the Bay Area is well-positioned to continue the evolution into the age of nanotechnology.

"Given the cluster of leading companies and universities in the Bay Area, the region is well-positioned to both discover the breakthroughs that will usher in the age of nanotechnology and to take commercial advantage of these discoveries and breakthroughs," said Juri Matisoo, Vice President of Technology Programs for the Semiconductor Industry Association which is headquartered in San Jose.

"A strength of research and development effort in the Bay Area is the large number of scientific collaborations between its public and private institutes," said Hans Coufal, manager of science and technology research for IBM's Almaden Research Center. "The recognition that we can accomplish more when we work together rather than individually helps make the Bay Area a vital force in the development of exciting new technologies at the nanoscale."

Indeed, the University of California at Berkeley, Davis, and San Francisco, the Lawrence

Nobel laureate physicist Richard Feynman is credited with sparking the nano revolution with his *There's Plenty of Room at the Bottom* ***speech in 1959.***



Berkeley National Laboratory, the Lawrence Livermore National Laboratory, the NASA Ames Research Center, Sandia National Laboratories, Stanford University, the Stanford Linear Accelerator Center, and SRI International –- these are all names that burn brightly in the pantheon of world-renowned research institutions. To this glittering list, add the names of such highly acclaimed research companies as IBM, Hewlett-Packard, Lockheed-Martin, Sun Microsystems, and the Palo Alto Research Center (PARC), plus the new stars of biotechnology, Alza, Bayer, Chiron, Genentech, Gilead Sciences, and Roche Bioscience.

Scientists and engineers within these Bay Area research facilities played central roles or made significant contributions to many of the greatest scientific achievements and technological breakthroughs of the past 50 years. With a talent base of skilled and highly trained researchers, state-of-the-art hardware and software resources, access to machines and instrumentation with capabilities found nowhere else, and a support infrastructure unmatched by any other region in the United States, these facilities have already become hot-beds of nanoscience activity.

To reach out and communicate with the general public and potential investors in nanotechnology R&D, representatives of the Bay Area's top research facilities have organized the Bay Area Science and Innovation Consortium (BASIC). Through BASIC, they are sponsoring this report. It will explain where nanotechnology stands today, where it is headed tomorrow, and what challenges lie ahead before reaching that destination. Most importantly, this report will give examples of what has been accomplished to date to meet these challenges by the men and women in the research and development community of the San Francisco Bay Area.

What Is Nanotechnology?

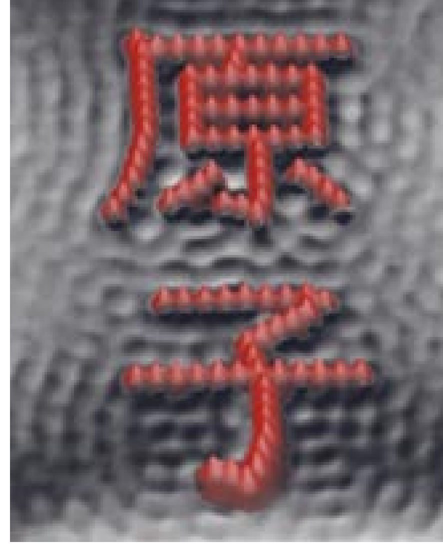
In 1959, the late physicist Richard Feynman, widely regarded as one of the greatest scientists of the 20th Century, gave a speech before the American Physical Society entitled: *There's Plenty of Room at the Bottom*. In this speech, he exhorted the scientific community to begin serious research investigations into manipulating and controlling things on a nanosized scale. He listed several critical economic applications as reasons to do this and speculated that with nanoresearch "an enormous amount can be done in principle."

As we move into the new millennium, research into manipulating and controlling things on a nanosized scale is well underway. Already it has begun yielding solid technological benefits, and there are a great many more waiting in the wings.

Even those not tuned into the high-technology scene no doubt have heard about nanotechnology. Feynman is not the only Nobel laureate to tout its potential. Other proponents include Richard Smalley of Rice University, winner of the 1996 Nobel Prize in chemistry for his discovery of fullerenes— the cagelike structures of carbon atoms, the most famous of which is carbon-60, the buckyball— and John H. Marburger, science advisor to President George W. Bush. In addition, popular novels, such as Neil Stephenson's *The Diamond Age*, have portrayed the near magical wonders of being able to program matter, while others, most notably Michael Crichton's *Prey*, have imagined potential dangers. How much of all this is to be believed? First, it is necessary to define what exactly constitutes "nanotechnology."

Under the most strict definition, nanotechnology is technology that operates anywhere within the nanometer length of scale. One nanometer is one billionth of a meter. This is the realm of the atom, the smallest unit of an element. Atoms serve as the basic building blocks of all materials. Although they can be split or fused under extreme conditions, for biological and virtually all other chemical reactions they remain intact. The smallest of all the different types of atoms is hydrogen, which measures about 0.10 nanometers in diameter ("about" because atoms are nuclei wrapped in electron clouds that don't have distinct boundaries). This means that about ten atoms of hydrogen strung together side-by-side in a straight line will measure about one nanometer across.

The purview of nanotechnology lies in a region ranging from one to about 100 nanometers. This is midway between the macroscopic scale of our everyday world, where bulk properties emerge from the collective behavior of trillions of atoms, and the world of individual atoms where quantum mechanics rules. Travel here and, like Alice in Wonderland, you find the rules that govern the behavior of materials in our macroscopic world no longer apply. A dropped object will fall? A liquid hitting a surface will spread out? Water will freeze at zero degrees Celsius and evaporate at 100 degrees Celsius? Not necessarily so. Here the rules for materials and their properties are waiting to be written by the scientists and engineers crossing into the nanotechnology frontier.



This image from IBM shows iron on copper atoms forming the Kanji characters for the word "atom" which translates as "original child."

Destinations and Challenges

It's been said that what we can do depends on what we can make. Under nanotechnology, what we can make might be limited only by the power of our imagination. This then is the ultimate destination of nanotechnology. The nanoworld has always shaped the visible world around us, and now we are venturing into that frontier to study it and learn how to use it to our advantage.

Practical nanotechnology was born in the early 1980s, when two IBM scientists in Switzerland invented the scanning tunneling microscope (STM), a remarkably simple instrument that produces unprecedently detailed images of electrically conducting atomic surfaces. The atomic and magnetic force microscopes, also IBM inventions, extended atom-scale vision to non-conducting surfaces and enabled direct viewing of surface forces, such as magnetism and friction.

Within a few years, scientists worldwide were exploring the nano frontier. In 1990, Don Eigler of IBM's Almaden Research Center demonstrated that the STM could be used not only for imaging, but also for positioning atoms. His spelling of the IBM logo in 35 xenon atoms was the first demonstration of nanotechnology at work and immediately became a popular symbol of nanoscale precision.

Today, nanoresearchers are taking a two-pronged approach to making nanodevices. The "top-down" approach aims at continuing to shrink today's devices and machinery by improving existing techniques and incorporating such recent technological developments as x-ray lithography and electron-beam writers. The "bottom-up" approach will attempt to emulate Nature by stimulating atoms and molecules to self-organize or self-assemble into complex systems that will function as devices and machines, just as they do in biological cells.

Each approach faces its own challenges. Extending top-down manufacturing techniques to atomic scales appears to be increasingly difficult and expensive. As for Nature's self-assembled structures, they typically take a relatively long time to form and are often fragile by industrial standards. Nanoscience today is evenly divided between the two approaches, and the expectation is that hybrid approaches which incorporate self-assembly into existing top-down technologies will emerge.

Whichever approach or combination of approaches to nanotechnology proves successful, *At Berkeley Lab's Molecular Foundry, qualified researchers from the Bay Area and across the nation will have access to state-of-the-art nanofabrication tools. New multidisciplinary centers such as this will serve as entrance keys to the Age of Nanotechnology.*

it is widely believed by those who are knowledgeable that nanotechnology will one day touch upon all aspects of daily human life. In its 2001 report "Societal Implications of Nanoscience and Nanotechnology," the NSF estimated that by 2015 – now little more than a decade away – nanotechnology's market impact would exceed $1 trillion. Specific business sectors expected to see the largest benefits include manufacturing ($340 billion), electronics ($300 billion), pharmaceuticals ($180 billion), energy ($100 billion), chemical plants ($100 billion) and transportation ($70 billion). Venture capitalists, industry analysts, and other prognosticators see valuable nanotechnology applications in tools, materials, devices, electronics, environmental monitoring, and the biomedical fields.

Several member organizations of BASIC are primed to tackle the scientific challenges posed in one or more of these areas, and in many cases have already made respectable progress. What follows are some examples of what has already being done and what could be accomplished in the near future.

Tools

Among the BASIC members with capabilities for applying nanoresearch to energy technologies, perhaps the most extensive menu of programs currently resides at the Lawrence Berkeley National Laboratory (Berkeley Lab), a DOE national laboratory managed by the University of California (UC). Overlooking the San Francisco Bay from the hills above the UC Berkeley campus, Berkeley Lab conducts non-classified scientific research in a broad range of scientific disciplines, including computing, biology, chemistry, solid state physics and the materials sciences. Much of its nanoresearch is now being carried out under the aegis of The Molecular Foundry, one of five new centers for nanoscience that have been established by DOE.

The Molecular Foundry will be a DOE national user facility, meaning its resources will be made available to qualified users throughout the country. Though open now, The Molecular Foundry won't begin full-scale operations until 2006, when construction of its new building is complete.

With its proximity to other national user facilities located at Berkeley Lab — the Advanced Light Source (ALS), the nation's brightest source of soft x-rays for research; the National Center

X-ray light beams such as those generated at Berkeley Lab's Advanced Light Source are expected to play a crucial role in the characterization and fabrication of nanodevices. (image courtesy of Berkeley Lab)

for Electron Microscopy (NCEM), home to the world's highest resolution electron microscopes; and the National Energy Research Scientific Computing Center (NERSC), a leader in scientific supercomputing –- The Molecular Foundry offers a wealth of opportunities for the development of "soft" (biological and polymer) and "hard" (inorganic and microfabricated) nanostructures and their integration into complex functional assemblies.

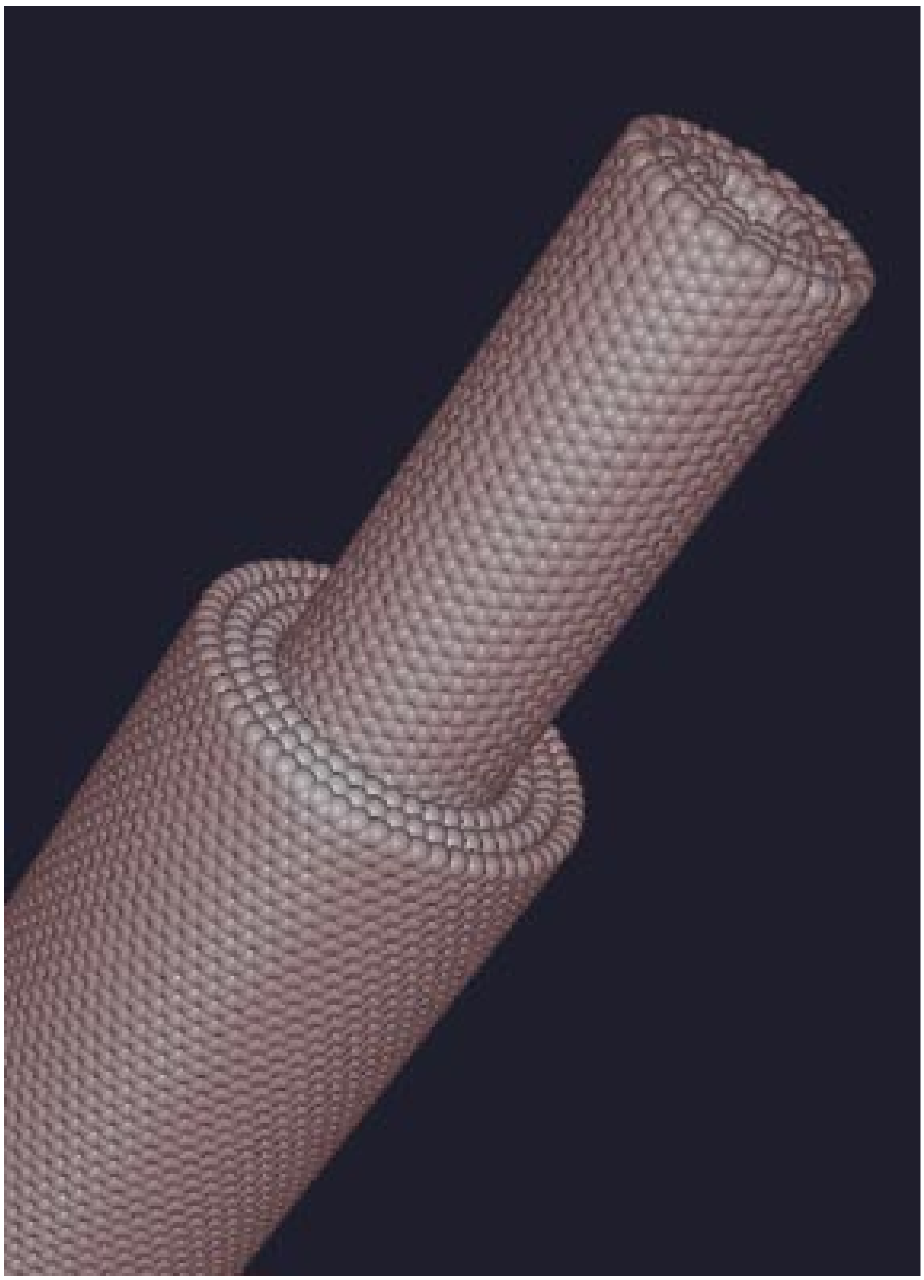
"Success in the development of nanotechnology will require that investigators have access to a breadth of facilities," said Paul Alivisatos, director of The Molecular Foundry, who, like most of the principal investigators associated with The Molecular Foundry, holds joint appointments with both Berkeley Lab and UC Berkeley.

"The idea behind The Molecular Foundry is to give everybody in the nanoresearch community the tools to make new molecules and nano-sized objects."

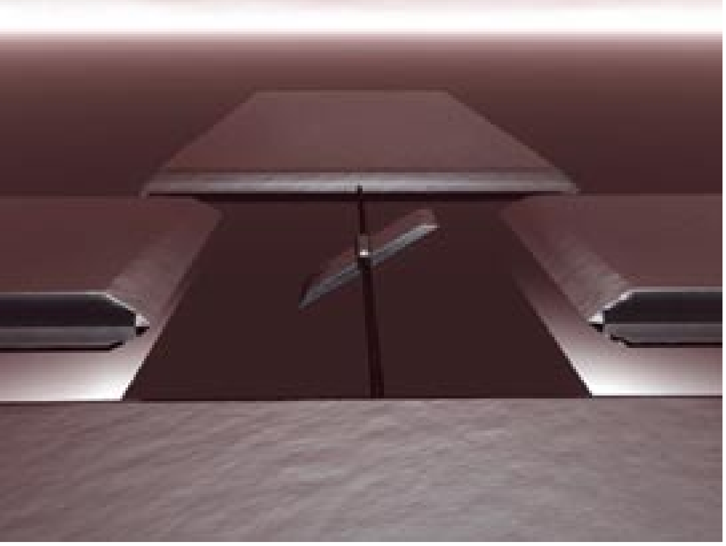
BASIC also provides a door into the National Science Foundation's (NSF) major nano-initiative –- the National Nanofabrication Users' Network – through another world- class Bay Area research institute, Stanford University. Under the NSF initiative, Stanford established the Stanford Nanofabrication Facility as a "hands-on" laboratory to serve as "the ultimate sandbox" for the development of micro- and nanomachines. With a full range of micro- and nano-fabrication capabilities and 100 clean room spaces plus experienced on-site staff, the Stanford Nanofabrication Facility is open to qualified researchers from industry, government and academic organizations.

Materials

In Neal Stephenson's acclaimed science fiction novel, *The Diamond Age*, nanotechnology is the basis for remarkable machines called "matter compilers," which are capable of creating just about any object a programmer can imagine, constructing these objects atom-by-atom. Through nanotechnology, a blank sheet of paper becomes a voice-activated wireless Internet connection, human bodies are enhanced with bioelectronic implants and a supercomputer is contained within a little girl's primer. To be sure, this is speculative fiction far beyond the fringe of foreseeable possibility. However, even the most conservative scientific and engineering seers predict that nanotechnology will revolutionize the field of materials science.



Carbon nanotubes offer a full range of electrical and thermal conductivity properties, are about a hundred times stronger than steel, and are more durable than diamonds. (image courtesy of Alex Zettl)



Berkeley researchers have used carbon nanotubes and etched silicon to build the world's smallest synthetic motor (image courtesy of Alex Zettl)

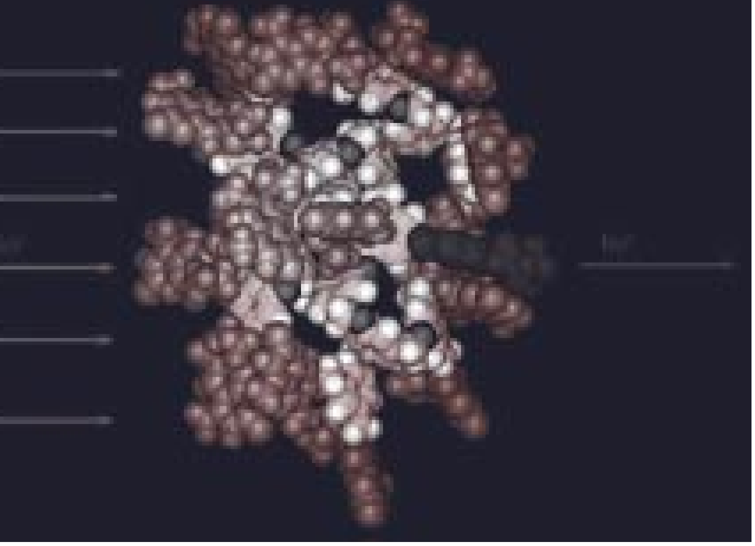
A major thrust of the nano-sized materials already underway at Berkeley Lab's Molecular Foundry focuses on nanotubes, hollow elongated macromolecules that form cylinders with a typical diameter about 100,000 times more narrow than the diameter of a human hair. The earliest nanotubes were made from pure carbon. Formed naturally in the sooty residue of vaporized carbon rods, they were a form of fullerene molecules joined in a graphite-like mesh of hexagonal rings that resembled rolled-up chicken wire. Later, scientists at Berkeley and elsewhere learned to make nanotubes out of other materials, such as the semiconductors boron nitride and gallium nitride. Any compound with a propensity for forming graphite-like sheets is considered potential nanotube material.

Nanotubes offer a full range of electrical and thermal conductivity properties (they conduct heat better than any other known material), plus they're about 100 times stronger than steel and more durable than diamonds. Their potential as building blocks for nanotechnology is nothing short of mind-boggling. If all the nanotube circuits that could be packed into a one-half-inch cube were to be laid out end-to-end, they would stretch some 250,000 miles. For all these reasons and more, the ability to mass-produce a wide variety of nanotubes with tailored properties would impact a wide range of technologies.

"In almost any technological application you want to think of, nanotubes probably will have an impact," said Alex Zettl, a physicist with Berkeley Lab's Materials Sciences Division (MSD) and the UC Berkeley Physics Department. "The most exciting thing about working with nanotubes is that a lot of structures we can now make in the laboratory are very relevant to everyday life. Nanotubes could be used as structural materials, electronic materials and chemical sensing devices."

Zettl and his research group have made an assortment of amazing new nanotube structures including what may be the world's smallest human-made bearings and mechanical switches, the world's smallest room-temperature diodes, and the first insulated nanowires, consisting of a chain of carbon nanotubes fused together to form a wire that is sheathed within nanotubes made of boron nitride. Other researchers at the Molecular Foundry have used nanotubes to create ultraviolet light nanolasers and striped nanowires made up of at least two different kinds of semiconductors.

Nanotubes are by no means the only macromolecules being researched for possible nanotechnology applications. Also high on the list are a new class of polymerized macromolecules



Dendrimers are a class of polymerized macromolecules that have the potential to perform a wide variety of chemical tasks, including the harvesting of light as a source of energy. (image courtesy of Jean Fréchet)

that have the potential to provide the most exquisitely tailored forms and functions ever realized outside of Nature. These macromolecules are called dendrimers from the Greek *dendros*, meaning trees, and *meros*, meaning part. Think of a tree in which each of its branches divides into two new branches after a certain length. This continues repeatedly until the branches become so densely packed that the canopy forms a globe. In a dendrimer, the branches are interlinked polymerized chains of molecules, each of which generates new chains.

The surface of a dendrimer globe bristles with numerous chain-ends, like fuzz on a ball of yarn. During synthesis, these chain-ends can be designed to perform specific chemical functions. For example, they may be electrically charged so that the entire dendrimer functions as an electrolyte. Other features, including the external size and internal architecture of a dendrimer can also be controlled during synthesis. This makes possible the creation of interior cavities or channels with properties different from those on the exterior and opens the door to dendrimers serving as vessels or hosts for guest molecules.

Already a class of dendrimers has been developed by Jean Fréchet, a UC Berkeley chemistry professor who heads the Organic and Macromolecular Facility at The Molecular Foundry, that can be used as transportation vessels for shuttling proteins into cells. These microscopic polymer beads can be embedded with a protein – a vaccine antigen, for example – and made large enough to attract the attention of the immune system's scavenger cells, which engulf them and try to digest them with acid. The acid causes the beads to fall apart, forming thousands of small molecules that immediately swell and explode the cell's digestive chamber before the acids have a chance to degrade the antigens. This technique eliminates a big problem for protein antigens: they are often destroyed by cell digestive acids before they can be used for display on the cell surface. Without such display, the immune system cannot detect the presence of the foreign protein.

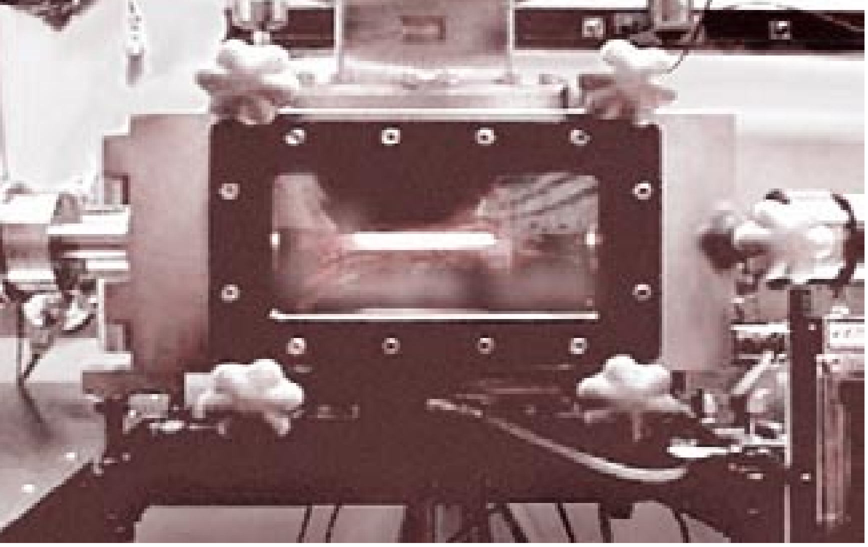
"Our technique skirts the disadvantages of today's injectable vaccines, which employ deactivated viruses to ferry antigens into the cell interior," said Fréchet. "It is not clear whether deactivated viruses can always be turned into a vaccine. Our technique is a general delivery system that can be adapted to many different proteins."

Fréchet and his colleagues have also designed light-harvesting dendrimers that can perform some of the early functions of artificial photosynthesis. Photons are gathered over a wide area on the surface of the dendrimer through chain-ends that behave like antennae. Absorbed photons are then funneled down into the core, which consists of a single chromophore that can either emit the photons back out as a single color of amplified light or convert them into electrical or chemical energy. Dendrimers should also be applicable for the storage of information as part of a nanoelectronics systems.

For materials scientists, the expression "beauty is only skin-deep" is more than an aphorism, it's a way of life. The chemistry of any given material is controlled by the miniscule fraction of atoms on its surface that interface with the external environment, including the surface atoms of other materials. For this reason, it has been said that material surfaces and the coatings that protect them or enhance their chemical interactions play major roles in defining a society's standard of living. No wonder then that surface coatings made from nano-sized crystals are drawing mountain-sized interest from the nanotechnology research and development community.

Nanocrystals are aggregates of anywhere from a few hundred to tens of thousands of atoms that combine into a crystalline form of matter known as a "cluster." Typically under 10 nanometers in diameter, nanocrystals are larger than molecules but smaller than bulk solids and therefore often exhibit physical and chemical properties somewhere in between. Surface coatings made from nanocrystalline materials stand to be stronger, harder, lighter and more flexible than today's best coatings. They may also be biodegradable. Nanocrystal coatings also promise to eliminate friction, the number one enemy to machinery and other devices. Furthermore, through the combination of nanocrystal coatings and nanocomputing, manufacturers will have the potential for creating "smart" surfaces that can respond to changes in their surrounding environment. Imagine nanocrystal particles embedded in your most prized gadgets that are programmed to recognize your DNA and will function only for you or those whom you designate as authorized users. We aren't there yet, but several of the member organizations in BASIC are already taking steps towards those goals.

At SRI International, a nonprofit research organization that began in 1946 as the Stanford Research Institute then changed its name in 1977, a collaboration has been formed with the NanoGram Corporation (previously Neophotonics) to develop and commercialize new nanoscale materials for a variety of applications. Under the leadership of Yigal Blum and Brent MacQueen, and Nobe Kambe and Christian Honeker at NanoGram, collaboration researchers are now exploring



At SRI International, researchers are using infrared laser light inside chemical reaction chambers as a means of economically synthesizing a wide variety of nanopowders. (image courtesy of SRI)

a variety of approaches to creating polymeric nanocomposites, a combination of polymers and nanocrystals that can bestow unique new properties to the base materials and can be processed in much the same manner as plastics.

"The effective dispersion or selective placement of precipitations of nanocrystals into polymers poses numerous challenges," said Blum. "Overcoming these challenges, however, would pave the way for the creation of novel optical materials that would include refractive engineering and photonic crystal applications, coatings with functional and reinforcement properties, and a new crop of structural plastics and organic resins."

Said MacQueen, "An attractive feature associated with the additional functionality is maintaining the transparency of the polymers, which is a critical issue in many optical devices as well as in applications where clarity is required for decorative or practical reasons."

Blum and MacQueen believe that laser pyrolysis synthesis, a technique in which pulses of infrared laser light are used to induce controlled chemical reactions, is especially promising as a way to synthesize a broad range of nanopowders on an economically viable scale.

Developed by NanoGram and deployed in its fully-scaled "Nano-Particle Manufacturing" (NPM™) system, this version of laser pyrolysis synthesis uses a precisely defined chemical reaction zone in which gases are combined to form simple or complex nanoscale crystalline compounds. These compounds feature narrow size distribution and negligible agglomeration, and typical particles range in size from 15 to 50 nanometers, depending on the processing parameters.

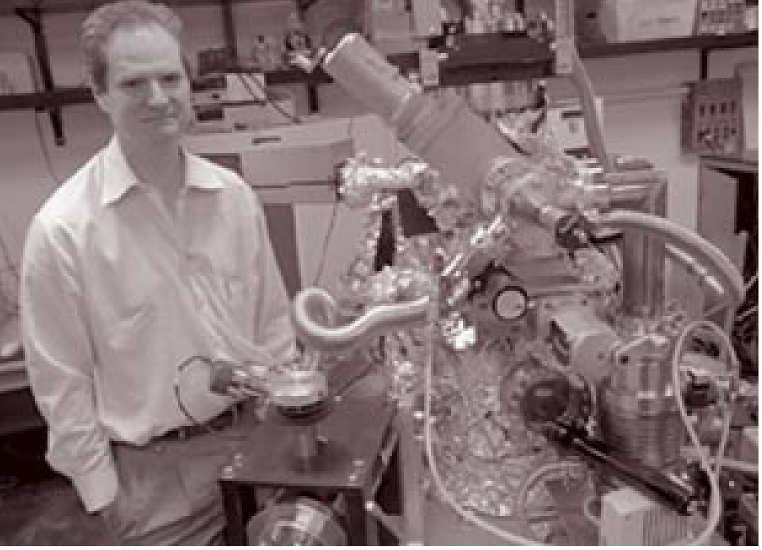
They should be directly applicable to the development and application of new phosphors, catalysts, energy-generating materials and ceramics.

"Photonic devices based on refractive index engineering are on the horizon, and photonic crystal structures are within reach," said Blum.

For materials scientists, nanocrystals are expected to serve as more than surface coatings, they are also expected to serve as the stuff from which exotic new materials are made.

"Nanocrystals are particularly attractive as building blocks for larger structures because it's possible – even easy – to prepare nanocrystals that are highly perfect," said Paul Alivisatos, director of Berkeley Lab's Molecular Foundry and a professor of chemistry at UC Berkeley. Alivisatos is widely regarded as one of the leading lights in the burgeoning field of nanocrystals grown from

These images show the variety of shapes and sizes that nanocrystals can be made to assume. The rod-shaped nanocrystals to the far left can be stacked for possible use in LEDs, while the tetrapod to the far right should be handy for wiring nano-sized devices. (image courtesy of Paul Alivisatos)



IBM's Almaden Research Center occupies a 690-acre hilltop campus in San Jose and has a staff of more than 400. It is one of eight IBM Research Division facilities worldwide and a center of nanoscience activity. (images courtesy of IBM Almaden Research Center)

Chemist Paul Alivisatos is a leader in the development of nano-sized crystals that could serve as building blocks for electronic devices a few billionths of a meter in size. (image courtesy of Berkeley Lab)

semiconductors. He and his research group have shown that because a nanocrystal is virtually all surface and no interior, a semiconductor nanocrystal's properties can vary considerably as the crystal grows in size.

"By precisely controlling a semiconductor nanocrystal's size and surface, its properties can be tuned," Alivisatos said. "You can tune the bandgap, you can tune how it conducts charge, you can change what crystal structure it resides in, you can even change its melting temperature."

One of Alivisatos' big breakthroughs came when he and his research group discovered that spherical nanocrystals made from a core of cadmium selenide inside a shell of cadmium sulfide could, depending upon their size, be made to emit multiple colors of light. This opened the door to a number of potential applications including the use of these spherical core-shell nanocrystals as highly effective fluorescent labels for the study of biological materials.

The next big breakthrough came when Alivisatos and his group were able to grow two-dimensional cadmium selenide nanocrystals that were shaped like rods. Prior to that, the nanocrystals that had been reported had all been one-dimensional spheres. Demonstrating the ability to grow semiconductor nanocrystals into two-dimensional rods not only paved the way for a slew of new potential applications, it also proved that controlling crystal growth is the key to controlling shape as well as size.

Since then, Alivisatos and his group have been able to grow semiconductor nanocrystals in the shape of tear drops, arrowheads and even four-armed tetrapods. While these exotic shapes have no immediate application, they expand the possibilities of the things that might be built from nanocrystal blocks in the future. For example, when the tetrapod nanocrystals are dropped onto a surface they always land on three arms with the fourth arm pointing straight up. This should be a handy feature for the wiring of nanosized electronic devices.

UC Berkeley researchers are also participants in another major Bay Area collaboration that's conducting investigations into nanoscale materials and structures. This collaboration is the Center on Polymer Interfaces and Macromolecular Assemblies (CPIMA). It is an NSF-sponsored partnership that is hosted by Stanford University and includes researchers from IBM Almaden and UC Davis in addition to UC Berkeley. The mission here is to understand and control the structure, dynamics and function of polymers and other soft materials at micro and nanoscale dimensions.

Stuart Parkin, an IBM Almaden physicist, has used a sputtering technique to obtain the GMR effect in materials at room temperature in very small magnetic fields. (images courtesy of IBM)

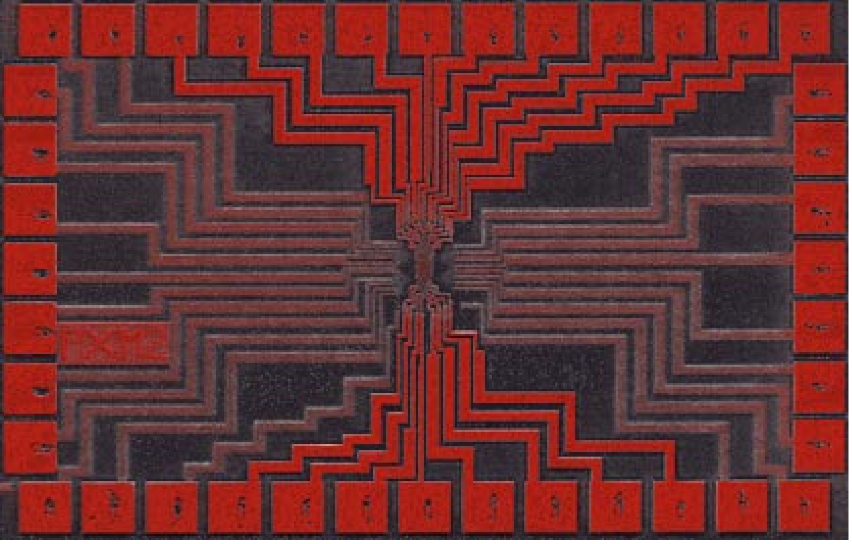
Other BASIC members with nanoresearch capabilities in materials science include the Lawrence Livermore and Sandia National Laboratories, SRI International, Hewlett-Packard and Lockheed Martin.

Devices

Creating and learning more about the unique properties of nanoscale materials is already leading to radically new types of devices with unprecedented abilities. The first widely successful nanotechnology product was introduced in 1997 at IBM's Almaden Research Center, a 690-acre hilltop campus in south San Jose. This product, a "giant magnetoresistive" (GMR) head, was a data-reading element made from a multi-tiered sandwich of thin metal layers, some magnetic and others only a few atoms thick. It would soon thereafter be used in all of the millions of hard-disk drives produced each year. Able to sense much smaller magnetic bits on the rapidly spinning hard disks than had ever been possible before, the GMR head enabled huge increases in disk-drive data density. This proved critical in the success of personal and enterprise computers, portable electronics, web applications and e-business.

The GMR effect was first seen in the late 1980s by two European scientists working independently. When they placed materials comprised of alternating very thin layers of several metallic elements in high magnetic fields, they saw electrical resistance changes greater than the 2- to 3- percent typical of the well-known "magnetoresistive" effect. While this discovery took the scientific community by surprise, few thought it could lead to any practical applications, since GMR was observed only at very low temperatures in the presence of very high magnetic fields, and in laboriously grown materials that cannot be mass-produced.

But IBM Almaden physicist Stuart Parkin and two groups of colleagues recognized that the GMR effect could be important if it would occur in easily made materials at room temperature and the very small magnetic fields (only a few times that of the Earth's magnetic field) created by tiny magnetic bits. Parkin was delighted when the first multilayers he made by sputtering – a fast process common in disk-drive manufacturing – showed GMR. Extensive experimentation then led the IBM teams to design nanostructures that achieved their goals.



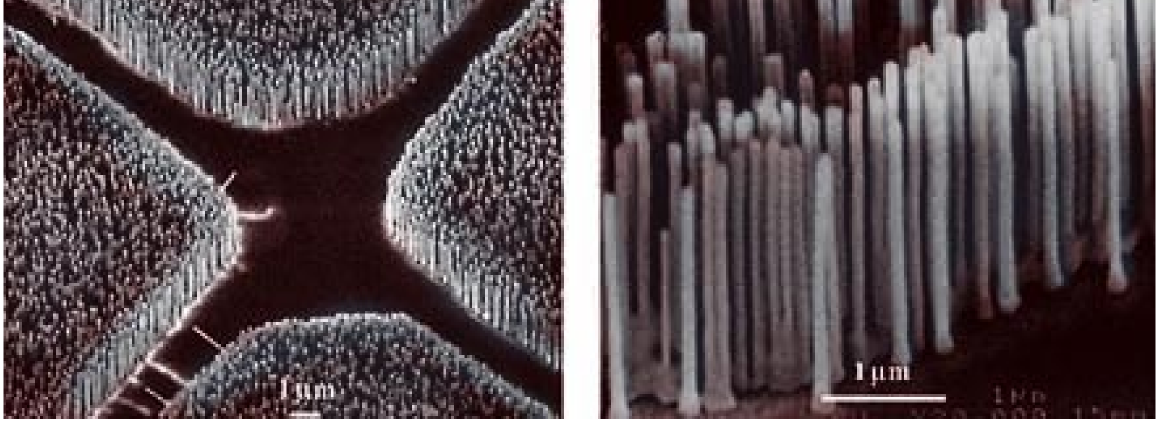
Magnetic Random Access Memory or MRAM exploits an effect called the magnetic tunnel junction to produce a fast, high-density memory chip. (image courtesy of IBM Almaden)

The key to the GMR head is the spacer layer of a non-magnetic metal sandwiched between two magnetic metals. As magnetic materials tend to align themselves in the same direction, if a spacer layer between them is thin enough, changing the orientation of one of the magnetic layers can still cause the other one to align itself in the same direction. Increasing the spacer layer thickness should cause the strength of such "coupling" between the magnetic layers to decrease. However, Parkin's team discovered instead that the coupling strength and magnetic alignment periodically swing back and forth as the spacer thickness increases by just a few atoms, going from being aligned in the same magnetic direction (parallel) to being aligned in opposite magnetic directions (anti-parallel).

A GMR device's overall resistance is relatively low when the layers are in parallel alignment and relatively high when in anti-parallel alignment. This is the key to sensing tiny magnetic bits due to the "spin-dependent" scattering of electrons. Electrical resistance arises when electrons are scattered within a material. By analogy, consider how fast it takes you to drive from one town to another. On a freeway, you might proceed rather quickly. But if you encounter heavy traffic, accidents, road construction and other obstacles, you'll travel much more slowly. When the magnetic layers in GMR structures are aligned anti-parallel, the resistance is high because "up" electrons that are not scattered in one layer can be scattered in the other. When the layers are aligned in parallel, the "up" electrons will not scatter much, regardless of which layer they pass through, yielding a lower resistance.

The success of the GMR head led to additional research in new types of novel nanoscale "spintronic" devices. Magnetic Random Access Memory (MRAM) is based on the magnetic tunnel junction, which uses an insulating spacer layer instead of the metallic spacer in GMR heads. The increased electrical resistance and GMR of the magnetic tunnel junction permits vertically oriented multilayered structures that are much more economical to make. MRAM promises to be a fast, high-density, non-volatile memory chip, possibly eventually becoming a universal memory that could replace all of today's memories, such as DRAM, SRAM and Flash. Several companies are well along in developing their initial MRAM products.

The next spintronic devices being researched use spin transistors to create and manipulate electrical currents containing only "up" or "down" electrons. Theorists have predicted that such devices could be much more energy efficient than traditional electronics. IBM Almaden and



These nanowire nanolasers which measure just under 100 nanometers in diameter are the smallest lasers ever made – far too small to be seen even with the aid of the most powerful optical microscope. (images courtesy of Peidong Yang)

Stanford are now collaborating to develop technology based on the creation, manipulation and detection of electron spin and spin-polarized electrical currents.

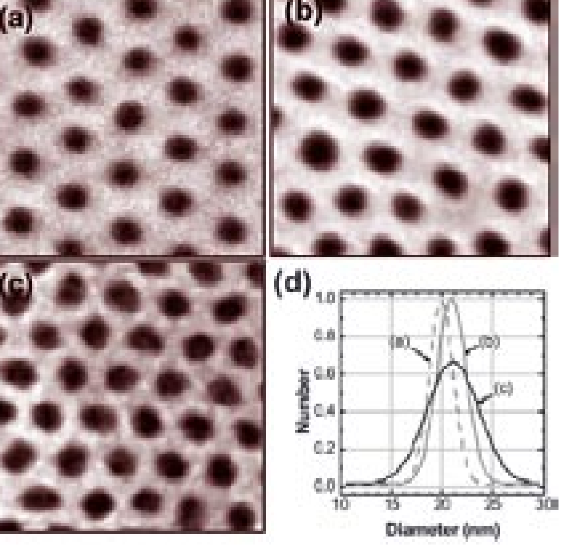
A Berkeley Lab-UC Berkeley scientist with a growing reputation for making nano-sized devices is Peidong Yang. He and his group first gained fame a couple of years ago when they produced one of the smallest lasers ever made – far too small to be seen even with the aid of the most powerful optical microscope. They called their device, which emitted flashes of ultraviolet light, a "nanowire nanolaser" and it measured just under 100 nanometers in diameter. By comparison, the tiniest solid-state lasers in use today are fashioned from thin films of either gallium arsenide or gallium nitride and generally run several microns thick, or about one hundred-thousandths of an inch.

The nanowire nanolasers were formed out of pure crystals of zinc oxide that grew vertically in aligned arrays like the bristles on a brush. These crystal wire "bristles" ranged from 2 to 10 microns in length, depending upon how long the growth process was allowed to proceed.

Said Yang at the time the discovery was announced, "The ability to produce high-density arrays of light-emitting nanowires should open up lots of possible applications that today's gallium arsenide devices can't do."

More recently, Yang and his colleagues used their nanowire production technique to synthesize nanotubes with diameters ranging between 30 to 200 nanometers from the prized semiconductor gallium nitride. Considered by many to be the next important semiconductor material after silicon, gallium nitride is a brilliant light emitter capable of operating at high temperatures and a leading candidate to be the key material for the next generation of high-frequency, high-power transistors. The major drawback to gallium nitride technology has been the cost of growing gallium nitride crystals. However, with the nanowire technique, the crystals can be mass-produced at a relatively low cost.

The gallium nitride nanotubes created by Yang and his colleagues have both an inner and outer surface to which other molecules, especially organic molecules, can readily attach, making them ideal candidates to serve as nano-scale chemical sensors. Because their surfaces are essentially transparent, these nanotubes could also be used as a cage to hold molecules in place for spectroscopic studies. Yang believes that gallium nitride nanotubes also lend themselves to



IBM used self assembly to build a nanocrystal computer memory device. After polymer molecules assemble into hexagons (a), the pattern is reproduced on silicon dioxide (b) which is then processed into silicon nanocrystals (c) that have maintained the hexagon pattern as shown by the histogram (d).

nano-scale techniques in fluidics and electrophoresis.

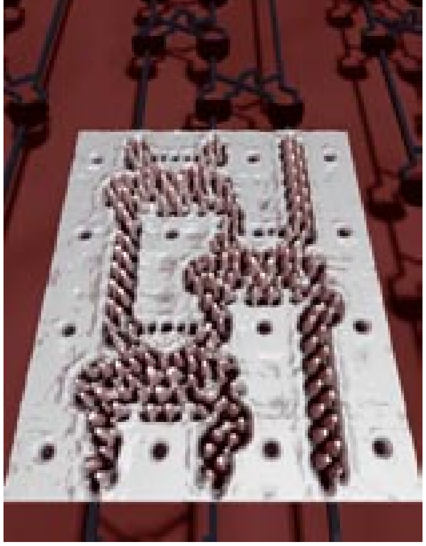
"These nanotubes could mimic ion channels like those in a biological cell, or they could be used to separate molecules in the same way as the microscale labs-on-a-chip," Yang said. His nanowire fabrication technique should work for making nanotube devices out of just about any semiconductor material.

Electronics

Ultimately, the area in which nano-scale capabilities may well have their biggest impact is information technology (IT). The important thing to remember about IT is that size matters: the smaller the device and the shorter the distance an electronic signal has to travel, the faster that device will be. Today's top computer chips are as fast as they are because some 50 million transistors can be crammed onto a square of silicon no bigger than a postage stamp.

The world's first digital, electronic computer was built by the United States during World War II and called ENIAC for Electronic Numerical Integrator and Computer. ENIAC took up about 1,800 square feet of space and weighed more than 30 tons. It was packed with 18,000 vacuum tubes, which were connected by more than 500 miles of wiring. Today, ENIAC's entire memory storage capacity could sit on a dime-sized integrated circuit, and the calculations that it could perform in 30 seconds (considered breathtaking then) can now be done in a few millionths of a second. For the past 40 years, integrated circuit manufacturers have been able to double the number of transistors onto a silicon computer chip every 18 months –- a shrinkage rate known as Moore's Law, after Intel co-founder Gordon Moore, who in 1965 presciently predicted the rate at which transistors would shrink in size.

Nanotechnology's biggest impact on electronics figures to come in two ways – improving the ability of today's top-down photolithography manufacturing techniques to make ever smaller circuit features, and enabling radically new types of circuits based on the actions of small numbers of atoms or molecules. Since the properties of any features smaller that about 50 nanometers (0.05 microns) will be ruled largely by quantum mechanics, their design will benefit greatly from the results of nanoscience experiments.



Using a technique called "molecular cascade," IBM Almaden researchers have constructed molecular electronic devices featuring the world's smallest computing circuits, such as the one shown here. (image courtesy of IBM Almaden)

Not surprisingly, the two BASIC members at the forefront of advanced electronics are IBM and Hewlett-Packard.

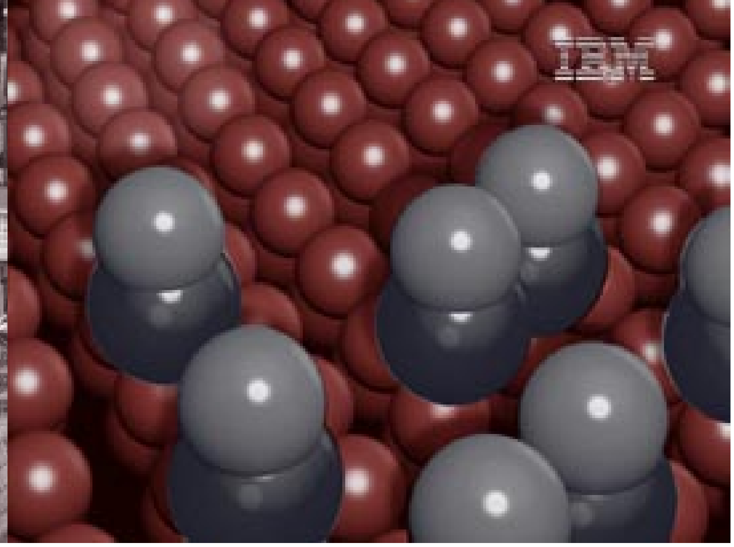
IBM Almaden scientists are exploring the use of two clever types of polymers to achieve nanoscale precision by incorporating self-assembly into conventional photolithographic processes. Inimers – molecules containing both an initiator and a monomer fragment for use in subsequent polymerization steps – have reduced the spacing between a stamped pattern of lines from 100 nanometers to 20 nanometers. After creating the lines with the inimer, scientists add a second polymer, which reacts with the exposed inimer at the surface to precisely increase the size of the lines, thus uniformly reducing the space between them.

IBM researchers in New York recently used a diblock copolymer designed at IBM Almaden to create arrays of uniformly-sized 20-nanometer-diameter silicon nanocrystals embedded between the gate and silicon substrate of a non-volatile "Flash" memory chip. A diblock copolymer is composed of two polymer segments joined into a single molecule. When a thin film of the copolymer is placed onto a substrate, the segments move around to be near others of its type, self-assembling into a precisely regular pattern that reflects the relative lengths of the segments. In both cases, traditional photolithography can then be used to create electronic features based on the self-assembled patterns. For applications requiring regular patterns of nano-scale features, these new nanoscale polymer processes may significantly improve microelectronics without incurring high tooling costs or risks associated with major process changes.

Another intriguing research area is molecular electronics, or moltronics, in which molecules serve as transistors. Given that molecules are only a few nanometers in size, billions or even trillions of molecular transistors could fit on a chip the size of those in use today if the construction, wiring and operation of single-molecule transistors becomes feasible.

Researchers at IBM Almaden have built and operated moltronic devices using a technique they call a "molecular cascade." In this technique, the movement of individual molecules across an atomic surface, a movement IBM likens to "toppling dominoes," enables the IBM researchers to construct digital-logic elements that are 260,000 times smaller than those used in the most advanced semiconductor chips now available.

"This is the first time all of the components necessary for nanoscale computation have been



IBM Almaden scientist Andreas Heinrich likens his group's technique for configuring electronic devices out of molecules to putting tennis balls next to each other in an egg carton. (images courtesy of IBM Almaden)

constructed, connected and then made to compute," said physicist Andreas Heinrich, one of the leaders of this project. "It is way smaller than any operating circuits made to date."

Heinrich and his colleagues made their device by using an STM in ultrahigh vacuum to create a precise pattern of carbon monoxide molecules on a copper surface. With the precisely controlled manipulation offered by the STM, the carbon monoxide molecules can be arranged on the copper surface in an energetically metastable configuration. This configuration can then be triggered to cascade into a lower energy configuration because of the weak repulsion between the carbon molecules when they are placed only one lattice space apart on a copper surface.

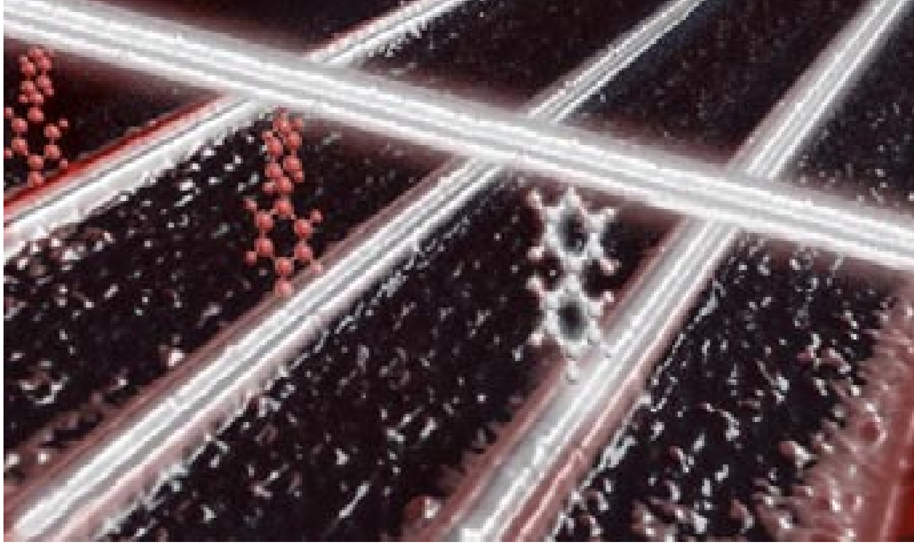
"It's like placing tennis balls next to each other in an egg carton," said Heinrich. "Since the tennis balls are slightly larger than the lattice spacing of the carton, they push against each other and can't nestle down into the hollows of the carton as deeply as they could if they were more widely separated."

In the digital computer logic language of 0s and 1s, where 0 represents "off/no" and 1 represents "on/yes," each cascaded molecular configuration carries a single bit of information so it can be thought of as a logical 1. Molecular configurations that do not cascade can be thought of as a logical 0. Logical AND/OR operations and other features needed for complex circuits can be created at the intersections of two cascades. The IBM Almaden researchers were able to design molecular configurations that acted as "crossovers," meaning two cascade paths crossed over each other, and "fanouts," meaning a single cascade could be split into two or more paths.

At this time, it takes several hours to assemble a single molecular cascade, and the cascade can only perform a calculation once. But the principle behind using molecular cascades in electronic devices has been established. The IBM Almaden researchers believe that it will be possible to make nanoscale molecular cascades using other fundamental interactions, such as electron spin, that would be resettable, permitting repeated calculations similar to the logic gates of today's computer circuitry.

Hewlett-Packard, through its HP Labs headquartered in Palo Alto, has achieved several noteworthy breakthroughs in moltronics. For example, researchers in HP Lab's Quantum Science Research (QSR) group have been able to create the highest density electronically addressable memory reported to date, a demonstration circuit — a 64-bit memory using molecules as switches

At HP Laboratories, researchers are developing molecular electronic circuits such as the one shown in this artist's concept. Depicted here are molecular switches connecting nanometer-scale wires in two different planes to form a cross-bar array. (image courtesy of HP Laboratories)



— that occupies a square micron of space, an area so tiny more than 1,000 of these memory bits could fit on the end of a single strand of a human hair.

In this same study, QSR researchers were also able to combine, for the first time, both memory and logic using rewritable molecular-switch devices. In addition, they were able to fabricate the circuits using an advanced system of manufacturing called nano-imprint lithography — essentially a printing method that allows an entire wafer of circuits to be stamped out quickly and inexpensively from a master copy. In this technique, molecules with unique electronic properties are used as the basis for high-density molecular devices and circuits. Electron beam lithography is used to make a master copy or mold of a chip from which copies can be stamped out similar to the way copies of text on paper are printed out in a press.

The master mold consists of eight platinum wires, running east-to-west across the surface of a silicon wafer, which are crossed in perpendicular fashion by eight wires running north-to-south. At each of the 64 points where the top and bottom wires intersect, the roughly 1,000 molecules sandwiched between them become a memory bit when a pulse of electrical voltage is applied to them. This memory is not only rewritable it is also non-volatile, meaning the memory is preserved even after the voltage is removed. HP Labs' QSR group is also able to put logic on the same circuit by configuring molecular-switch junctions to make a "demultiplexer" – a logic circuit that uses a small number of wires to address memory. Demultiplexers are essential in order for nanoscale memory bits to connect to microscale components and become commercially practical.

"It took a day to create the mold but it took just a few minutes to make an imprint," said QSR director Stan Williams. "In our lab, we aim to do nothing less than reinvent the computer. Computing efficiency has increased by a factor of about 100 million in the past 40 years, but there appears to be no physical reason why it can't be improved by a factor of a billion."

Hewlett-Packard is also pursuing "bottom-up" approaches to inorganic structures, using the strain from mismatched crystal lattice to form small islands or one-dimensional lines of material on the nanoscale. Combined with this bottom-up approach, the relatively coarse patterning obtained from "top-down" fabrication can position the islands where desired. In a related bottom-up study, the acceleration of chemical vapor deposition by a metal catalyst nanoparticle is used to form one-dimensional nanowires. These metal-catalyzed nanowires may be useful as the interconnecting bridges between conventional electronics and nanoelectronics.

Researchers from BASIC members UC Berkeley, UC Santa Cruz, and Stanford are central participants in a unique collaboration initiated by the Semiconductor Industry Association (SIA) called the Focus Center Research Program (FCRP). The goal of the $24 million FCRP is to explore nanotechnology alternatives that can be made ready for that inevitable time when microtechnology reaches its limit.

For the Bay Area, research under the FCRP is headquartered on the UC Berkeley campus at the Gigascale Silicon Research Center (GSRC), which was founded in 1998 to explore all the aspects of semiconductor design and testing needed to produce chips containing billions of circuits.

"The industry has been able to successfully follow, and even accelerate Moore's Law", said Juri Matisoo, SIA's Vice President for Technology Programs. "However, our design productivity has not kept pace, leading to a growing gap between what we are capable of manufacturing and what we are able to efficiently utilize. This gap will increase as we move to greater levels of integration absent the development of new design paradigms such as those explored by the Gigascale Center."

One of the critical areas being investigated at the GSRC is the challenge of combining analog and digital functions on a single nanochip. Computing is largely digital, but a device must interface with the real world through analog signals.

The GSRC is the first university basic research initiative that is jointly funded by private industry and the Defense Department. Said GSRC director Richard Newton, "The GSRC is really as much an experiment in the area of university-based collaborative research as it is in the research topics themselves. It involves close collaboration among faculty, with industry, and with other Department of Defense-sponsored research groups across many design technology disciplines."

Other BASIC members with research applicable to nanoscale computing include NASA-Ames, the Palo Alto Research Center, SRI International, Lawrence Livermore National Lab and Berkeley Lab.

UC Davis is home to NEAT – Nanomaterials in the Environment, Agriculture and Technology – a research effort aimed at applying nanotechnology to environmental remediation efforts.

Environment

The environmentalist Terence McKenna, writing for the *Whole Earth Review*, once called nanotechnology "the most radical of all green visions." As stated earlier in this report, by virtue of enabling manufacturers to produce goods at the molecular level, nanotechnology in the 21st century has the potential to eliminate much of the need for the wasteful industrial processes that dirty our air, foul our waterways and stain the landscape. However, nanotechnology is also expected to play an important role in cleaning up the toxic residues of the 20th century. The model for this cleanup effort is Mother Nature. Nature performs environmental remediation through microbial organisms that break-down or degrade ecologically harmful molecules into molecules that pose no threat. Through the development of nanotechnology, humankind has the potential to do the same thing with molecules that aren't biodegradable.

An emerging leader in the application of nanotechnology to environmental remediation is the University of California at Davis, which has established the NEAT program. NEAT stands for Nanomaterials in the Environment, Agriculture and Technology. It is a multidisciplinary research and education program directed by Alexandra Navrotsky, winner of the prestigious Benjamin Franklin Medal for her research on the thermochemistry of minerals, high-pressure materials, and the chemical and electrical properties of nanomaterials. She is widely regarded as one of the foremost pioneers in the fledgling field of nanogeoscience. Currently, her research focuses on the structure and stability of natural and synthetic nanomaterials and their roles in the geochemical transport of potential pollutants.

"In the geological realm, nanomaterials are important to understanding where reactions (critical to the environment) happen in the earth," she has said. One of the possibilities Navrotsky and other NEAT researchers, including Isabel Montanez, are investigating is the use of nano-sized dust to study global climate change, the movement of pollutants in the atmosphere and the weathering of minerals. Another NEAT investigation, led by Tony Wexler, centers on the role of airborne nanoparticles on global warming, agriculture and air quality. Airborne nanoparticles, also known as aerosol particles, are suspended in the atmosphere at various altitudes and in varying quantities around the planet. Aerosol nanoparticles may be an important factor for global cooling that counteracts the global warming effects of carbon dioxide.

"The spatial distribution of the heating and cooling effects is different from what it used to be," said Wexler. "And our understanding of these effects is very crude."

With a better understanding could come a "geoengineering solution" to global climate change, Wexler said. The NEAT program at UC Davis offers the unique capability of being able to provide information on the size and composition of particles down to 10 to 20 nanometers. In addition to global climate change, agriculture and air quality, the research at NEAT is also expected to have an impact on clean rooms, pharmaceutical factories that produce aerosol powders, and other industries where occupational health and safety issues may arise from chemical production work.

Another institute that is putting nanotechnology to work on environmental remediation efforts is Sandia National Laboratories in Livermore, California. Created in 1956 to provide engineering support for the main Sandia laboratory facilities in Albuquerque, New Mexico, Sandia-California has developed expertise in a number of key nano-related areas including the development of sensor technology. One of the prime achievements in this area has been the development of µChemLab, a fully self-contained, portable, handheld device that can be used to sniff out, measure and analyze for the presence of a wide range of toxic molecules, including those that pollute groundwater, are emitted from smokestacks or might be used in a bioterrorism attack.

"There's a huge amount of information in chemical signatures that the world is not making use of," said Sandia California chemist David Rakestraw, "because it's too costly. It's also very difficult to extract out all of this information using traditional analytical chemistry in a laboratory."

The µChemLab systems contains two sets of sample concentrators, separators and detectors through which a sample material moves via a complex of miniature tubes, pumps and valves. A sample can be analyzed within 30 to 60 seconds. Future versions of the µChemLab systems are being designed to be able to simultaneously identify molecular samples of hundreds of different types of liquids and gases.

The biggest of all environmental remediation efforts is that of removing excess carbon from the atmosphere, the result of burning fossil fuels. The Berkeley Lab-UC Berkeley connection is and will continue to be at the forefront of this research with the proposal of a $3 million nanogeoscience program. This program will not only complement Berkeley Lab's Molecular Foundry, it is also

Nanotechnology has the potential to help clean up the toxic residues of 20th century industrial practices and greatly reduce future pollution. (image courtesy of US Forest Service)

projected to provide a virtual center that will electronically link several institutions across the nation where innovative nanogeoscience research is being carried out.

The idea behind the Berkeley Nanogeoscience Center is to give researchers who study how molecule-sized particles contribute to large-scale phenomena a common forum through which to interact and exchange ideas.

"People who study aerosols don't talk with people who study oceanic particles who don't talk with people who study soil particles," said Glenn Waychunas, a scientist in Berkeley Lab's Earth Sciences Division and one of the leaders behind this proposed nanogeoscience center. "We need to bring these different disciplines together."

One of the principle nanogeoscience areas in which investigations are already underway at Berkeley Lab and UC Berkeley is ocean-based carbon-sequestration, or how seawater captures atmospheric carbon. Seawater teems with tiny particles containing nanoscale iron molecules that help regulate the growth of phytoplankton. This, in turn, influences the exchange of carbon dioxide between the ocean and the atmosphere. Understanding how phytoplankton acquire and use iron will help explain how oceans capture atmospheric carbon, but, at this time, scientists don't know where these nanoscale iron molecules originate nor how to manipulate them.

"There is a black hole with regards to this research," Waychunas said. "Oceanographers generally study particles that measure 0.2 microns and larger, which means a lot of nanoscale particles are not examined, particularly with respect to formation mechanisms."

Other investigations underway are looking into how nanosized minerals perform soil remediation through the capture of toxins such as arsenic, copper and lead. There are several different mechanisms. Some toxins weakly adhere to particles through electrostatic forces while others precipitate onto a particle's surface, forming chemical bonds that are more difficult to undo. Even more troublesome is the phenomenon known as "aggregation," in which a precipitated toxin becomes sandwiched between the grains of a particle. Learning how these processes work on the nanoscale could greatly improve the effectiveness of remediation efforts.

Another strategy being examined links nanogeoscience with biomimetics, the design of drugs and other substances that mimic biological processes. The goal here is to manipulate microbes into producing nanosized minerals of specific sizes and shapes that most efficiently bind with toxins.

"We need to study the unusual properties of natural materials at the nanoscale, and we need to explore how these properties relate to carbon sequestration, plant nutrient transfer, toxic agent entrapment and many other geochemical cycles," Waychunas said.

An interesting wrinkle along this line of nanogeoscience inquiry was the recent results of Stanford University researchers who used ordinary alfalfa plants as miniature factories for the production of gold nanoparticles. Alfalfa has a natural, physiological need to extract metals from the soil, especially gold, which the plant stores in the form of nanoparticles. This is a much more efficient and environmentally benign means of producing gold nanoparticles than any of the chemical synthesis techniques now being deployed.

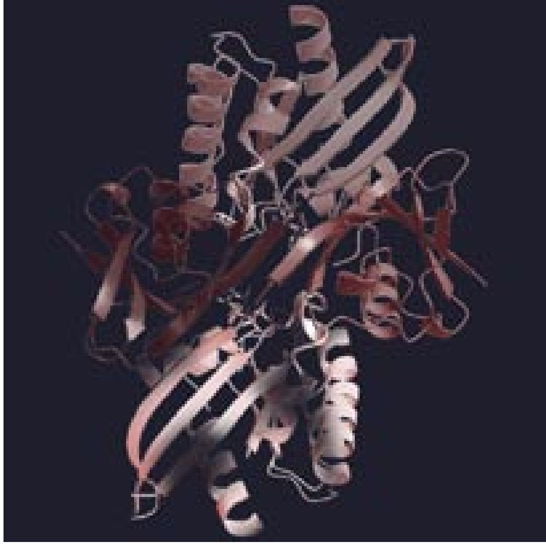
All plants use their roots to extract nutrients –- water, minerals and even heavy metals – from the soil, but alfalfa is a model system for studying the ability to extract gold from various growth media. The study was carried out using the unique properties of x-ray beams generated at the Stanford Synchrotron Radiation Laboratory (SSRL), another BASIC member facility that offers rich capabilities for nanoscale research.

Biomedical

In the 1966 film, *The Fantastic Voyage*, four men and a woman in a medical submarine are miniaturized and injected into a dying man's carotid artery in a desperate attempt to destroy a life-threatening blood clot in his brain. If their mission fails, the world will be destroyed. When Harry Kleiner wrote the original screenplay (later novelized by Isaac Asimov), he could not have imagined that come the nanorevolution, the human element would have been unnecessary. A squadron of medically programmed nano-sized robots could have saved the day much more efficiently and safely, since the miniaturized humans in the movie operated under a strict time limit and had to be clear of the patient's body before they and their submarine returned to normal size.

Nanotechnology may never reach the stage where paramedical nanobots can patrol the human bloodstream, but experts agree that applications of nanoresearch are probably more advanced in the fields of biology and medicine than in any other fields at this time. For good reason. Nature has been operating molecular factories for many millions of years, factories in which complex

Proteins such as this are polymerized chains of amino acids that determine the shape and structure of living cells and also control the chemical reactions that keep those cells alive and functioning. (image courtesy of Sun-Hou Kim)



machines are assembled from nano-sized components and used to run the factory and manufacture other machines. These factories are living cells and the machines are the biological molecules we call proteins. The nano-sized components of these protein machines are polymerized chains of amino acids, the bead-like packets of chemical substances coded for by DNA's genes.

Proteins determine the shape and structure of living cells and also control the chemical reactions that keep those cells alive and functioning. There may be as many as a trillion different kinds of proteins on earth, each with its own unique shape and each with a specific job that is vital in some way to the health and well-being of the cell in which it serves. For a protein to do its specific job, its amino acids have to be strung together in exactly the right sequence and position, after which the entire assemblage will undergo a physical contortion into one of thousands of different structural motifs any one of which would make the surreal artist M.C. Escher proud.

This is a pretty impressive accomplishment when you consider that even a simple protein like hemoglobin, the protein that carries iron and oxygen atoms in red blood cells, consists of 146 amino acids. Many proteins are made up of more than 1,000 amino acids. It generally takes several thousand different types of proteins to create and maintain a single cell and these proteins must all work together like an elaborate, finely choreographed network of interdependent machines for the cell to function.

Given that Nature has so much experience at building molecular machines, it is only natural that nanoresearchers look to imitate this technology in the construction and operations of their own molecular creations. The results so far, even at this early stage, are cause for optimism.

It may be surprising for many readers to learn that among the most promising of the biomedical results are to be found at the NASA Ames Research Center, which is located south of San Francisco in the heart of Silicon Valley.

NASA Ames specializes in research geared toward creating new knowledge and technologies that span the spectrum of interests for its parent agency the National Aeronautics and Space Administration. NASA's spectrum of interests encompasses such areas as autonomous "thinking" spacecraft, safe and affordable aviation, and human exploration.

In each of these areas, advanced miniaturization through nanotechnology is expected to play a critical role. Possible applications include distributed sensor networks of ultrasmall probes

Vision Chip, developed at NASA-Ames, features an implanted array of carbon nanotubes that could restore vision to patients suffering from macular degeneration, the number one cause of blindness in the elderly. (image courtesy of NASA-Ames)

on planetary surfaces, micro-rovers for collecting samples, and perhaps even an entire fleet of microspacecraft. With this in mind, NASA Ames began its Center for Nanotechnology in 1996 under the direction of physicist Meyya Meyyappan.

"Nanotechnology presents whole new opportunities to build device components and systems for entirely new space architectures," Meyyappan has said. "We're looking at a variety of nanoscale materials, but first and foremost at carbon nanotubes."

One of the most ripe of the opportunities referred to by Meyyappan is in the realm of biosensors and detectors that serve NASA's astrobiology interests. Researchers at the NASA Ames Center for Nanotechnology recently completed a grant from the National Cancer Institute to develop biosensors based on carbon nanotubes for cancer diagnostics.

"NASA has a history of developing technologies in electronics, sensors and systems for its missions, which also find applications in the commercial sector and which meet the mission needs of other agencies," Meyyappan said. "After discussions with the National Cancer Institute personnel it became clear to us that our technology would apply well to cancer detection and diagnostics."

Under the grant, the NASA Ames researchers developed a protein-sized nanoelectrode array of multiwalled carbon nanotubes – a series of successively smaller nanotubes nested within one another like Russian dolls – that can detect low levels of target DNA with a sensitivity already comparable to laser-based fluorescence (today's gold standard for DNA sensors). These multiwalled carbon nanotube sensors are expected to become much better with further development.

"The quick and reliable detection of small amounts of DNA or RNA has become increasingly important in diagnostics," said Jun Li, one of the researchers who led this development. "Multiwalled carbon nanotubes, with well-defined nanoscale geometry, are attractive nanoelectrode materials for this purpose. They can be extremely sensitive yet inexpensive and present a wide electrochemical window, flexible surface chemistry and biocompatibility."

The NASA Ames researchers made their DNA biosensors by growing vertical arrays of aligned multiwalled carbon nanotubes on prepatterned microelectrodes using plasma-enhanced chemical vapor deposition. These nanotube arrays were then encapsulated in silica and polished to flatten the surface so that only the tips of the tubes were exposed.

As these DNA sensors can be tuned to detect specific DNA sequences, such as those which serve as the molecular signatures of cancerous cells or those belonging to pathogens that could be used in bioterrorism, potential applications include early cancer detection and homeland security.

Said Meyyappan, "The concept is a high-risk, high pay-off approach, completely novel to the mainstream medical research community and represents a potential breakthrough in sensor technology."

Other NASA Ames researchers are working to develop a means of detecting and sequencing single molecules of either DNA or RNA through the use of solid-state nanopores. These devices are silicon chips fabricated with channels or "pores" measuring less than five nanometers in diameter and length. Single molecules of nuclei acid can be transported through these pores via electrophoresis for electronic analysis at the unprecedented rate of a million bases per second.

"Nanopore-based analysis of nucleic acid polymers is revolutionary because no other technique can determine information content in single molecules of genetic material at such a high rate of speed," says project leader Viktor Stole, director of NASA Ames Genome Research Facility. "Since individual molecules are counted, the output is intrinsically quantitative and in principle may be used to analyze any polymer molecule, including proteins."

According to Stole, these nanopore devices will have the ability to sequence and identify genetic variation in the genomes of any biological organism. Successful development of the nanopore device will be a major boost for the practice of personal molecular medicine, that is, the ability to provide personalized drug prescriptions, and diagnosis and treatment of acquired and inherited human diseases.

At the NASA Ames Center for Nanotechnology, researchers are also investigating the use of modified microbial proteins as nanoscale architectural templates. The idea is to piggyback onto a protein called "heat shock protein 60," which features a double-ring structure and is able to self-assemble into highly-ordered hexagonal arrays. This piggyback action yields mesh-like lattices that could be used as the basis for nanoelectronic devices.

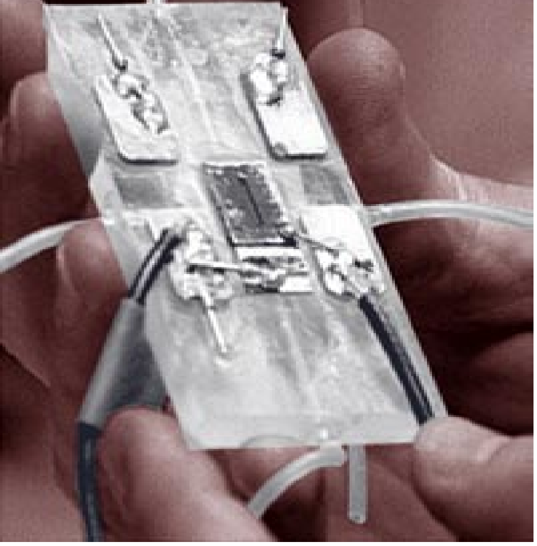
"We took a gene from a single-celled organism, *Sulfolobus shibatae*, which lives in near-boiling acid mud, and changed it to add instructions that describe how to make a protein that sticks to gold or semiconductors," said Andrew McMillan, one of the principal investigators on this project. "What is novel in our work is that we designed this protein so that when it self-assembles into a two-dimensional lattice or template, it also is able to capture metal and semiconductor particles at specific locations on the template surface."

The researchers quickly produced vast quantities of their heat shock protein by cloning it into a harmless form of *E. coli* bacterium. They chose to work with a protein from an extremophile microbe such as *Sulfolobus shibatae* because these proteins are durable enough to stand up to purification and other processing treatments even after they have been subjected to genetic engineering. The resulting 2-D mesh can hold an array of nanoparticles, each measuring less than one-tenth the size of the features on today's standard computer chips.

Perhaps the most intriguing of the possibilities at the Center for Nanotechnology is a technology called Vision Chip, which features an implantable array of carbon nanotubes that could restore vision to patients suffering from macular degeneration, the number one cause of blindness in the elderly.

Vision Chip consists of electrically-conductive carbon nanotube towers grown directly onto the surface of a silicon chip. Each tower in the array is connected to its own electrical circuit so it can receive telemetry signals generated by the pixels of a light detector that would be worn by the patient. Thousands of carbon nanotube towers can be placed on the chip in an array that matches the spacing of neuron nerve cells within the retina. The chip is designed to be implanted into the retina so the carbon nanotube towers come in direct contact with the retinal neurons. As an alternative, the chip can also be partially implanted into the retina after being coated with special growth factors to stimulate growth of retinal neurons toward the towers. Vision Chip has been demonstrated to be biocompatible with retinal cells and able to survive surgical handling and implantation forces.

At UC Berkeley, ground was recently broken for a new $162.3 million facility that will be one of the homes of the California Institute for Quantitative Biomedical Research. Called QB3 for short, this a joint program between UC Berkeley, UC San Francisco and UC Santa Cruz. UCB's new facility is scheduled for completion in 2006 and will house 40 laboratories, including an innovative Bio-Nanotechnology Center dedicated to the fabrication of bio-MEMS (MicroElectroMechanical Systems) and microrobotic devices on the microscopic and nanoscopic scale.



UC Berkeley researchers have developed a "bionic chip" which incorporates electronic circuitry onto a living cell. (image courtesy of UC Berkeley)

Several research projects slated for that center are already underway. They include development of a DNA-sensing chip that will be a quicker, easier and cheaper way to diagnose disease, detect evidence of bioterrorism or discover new drugs; a microscopic syringe for the painless injection of drugs that could simplify insulin injection for diabetics or ease delivery of pain medications on the battlefield; and a probe for studying human proteins to improve the effectiveness of therapeutic drugs and shed light on why some people are resistant to such drugs.

UC Berkeley researchers recently developed a "bionic chip," a device that incorporates electronic circuitry onto a living cell. The bionic chip employs a technique, called "electroporation," whereby the application of a precise amount of voltage creates pores on the walls of a cell through which researchers can safely introduce DNA, extract proteins or administer medicine. Potential applications range from the treatment of cystic fibrosis, diabetes and other genetic diseases to the testing of new therapeutic drugs.

Last, but by no means least, is the Lawrence Livermore National Laboratory (LLNL). Though known primarily as a nuclear weapons design laboratory, this enormous research facility also boasts a substantial number of non-weapons research programs. One such program is the BioSecurity and Nanosciences Laboratory where, among other projects, researchers are developing synthetic high-affinity ligands or SHALs. These small molecules possess some of the traits of natural antibodies. Most notably, SHALs can be designed to selectively bind to specific proteins. This means that SHALs can be set loose in the human body to target and remove the lethal molecules in toxins or pathogens, such as tetanus, anthrax or plague.

Working with researchers at UC Davis, LLNL researchers have also developed an instrument called "BAMS," for BioAerosol Mass Spectrometer. BAMS can collect and identify airborne particles at the single cell level in about 100 milliseconds, which is much faster than the blink of a human eye. So far, BAMS has been successfully tested on anthrax and is now being tested on tuberculosis.

Other BASIC members with nanoresearch capabilities in the biomedical fields include Berkeley Lab, SRI International and Integrated Nanosystems, a private spin-off of NASA.

"Any sufficiently advanced technology is indistinguishable from magic."

— Arthur C. Clarke's Third Law of Technological Development

Today's Challanges: Tomorrow's Opportunities

In his ground-breaking 1959 speech, "There's Plenty of Room at the Bottom," physicist Richard Feynman emphasized the word "plenty" because he said there was a huge amount of opportunity just waiting to be tapped at the nanoscale. These opportunities had not been seized, he said, "simply because we haven't yet gotten around to it."

As shown in this report, researchers at the various member institutes of BASIC are "getting round to it" today. As scientific investigation leads to increased knowledge and technological capabilities, it is becoming apparent that the opportunities at the nanoscale are even more plentiful than was envisioned by Feynman. Research results so far clearly point to potential benefits in the areas of tools, materials, devices, electronics and environmental monitoring, and in the biomedical fields. Other areas that also will surely see advances include energy, transportation, agriculture and communications.

You don't need the far-reaching vision of a Richard Feynman to appreciate that in the high technology arena of the 21st century, the next big thing is going to be very very small. If Feynman were giving his nanotechnology speech today, he might have titled it: *The Sky's the Limit.*

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