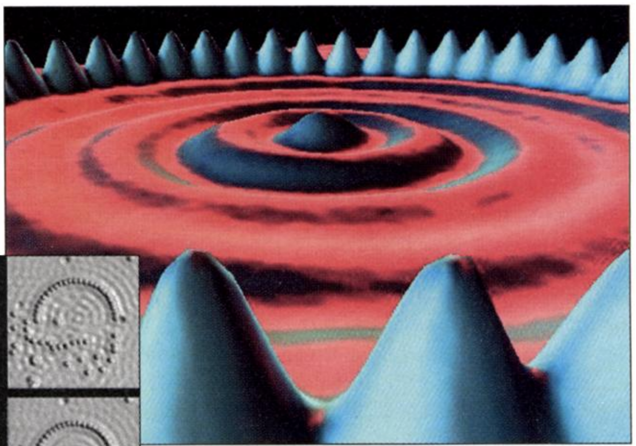
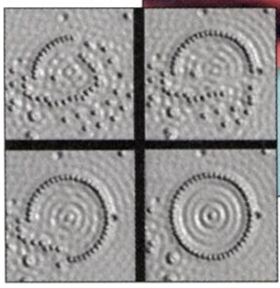
Atom-Scale Research Gets Real

Nanotechnology has spawned useful new materials and impressive technical feats. But the field's most grandiose dreams, and nightmares, remain the stuff of fiction





Atomic Stonehenge. In an early nanocoup, IBM researchers rounded up 48 iron atoms to make a "quantum corral."

In September, speaking to an audience of prominent researchers and government leaders at a meeting on the future impacts of nanotechnology, Michael Crow crossed a familiar line. "How many of you have read *The Diamond Age*?" the science policy expert and vice provost of Columbia University in New York City asked his listeners. The book, by science-fiction novelist Neal Stephenson, depicts a near-future world in which advances in nanotechnology make it possible to build essentially anything from scratch, atom by atom, leaving society to sift through the cultural ramifications of limitless choices. In response to Crow's question, a few hands fluttered in the air and quickly dropped. These people, after all, were nanotechnology's practitioners—not wide-eyed dreamers.

Crow wasn't promoting the book as a prophecy. He mentioned it, he says, to encourage researchers to think about their unique position at the dawn of a field that most in the room agreed will be a force in the coming century. But clearly his question touched a nerve. Since its inception, nanotechnology has been dominated by fiction, both unabashed hype and better grounded hope. Science-fiction writers have dreamt up lush scenarios of life with nanosized robots that do everything from building gleaming cities to reaming out clogged coronary arteries. Meanwhile, some researchers have been hard at work drawing impressive but equally fictional blueprints for arrays of tiny gears and pistons that could form the foundation of nanomachines—if anyone ever figures out how to assemble the thousands of atoms needed to build them.

This year, dystopian fiction came on the scene, as nanotech prophets of doom made bold new pronouncements of nanotechnology's potential to destroy humanity and called for either an end to research in the area or new guidelines to ensure that researchers don't accidentally wipe out life on the planet (see sidebar, p. 1526). "Nanotechnology seems to have this wonderful property of having the most extravagant favorable and unfavorable predictions," says Edward Tenner, a historian of science at Princeton University in New Jersey.

In response, many researchers at the cutting edge of dealing with matter on the near-atomic scale have become aggressively matter-of-fact, squirming at the suggestion of cornucopian nanofactories or even humbler mass-produced nanodevices. The nearby hurdles, they say, are challenge enough. "Nanotechnology is a vision, a hope to manufacture on the length scale of a few atoms," says Don Eigler of IBM's Almaden Research Center in the hills above San Jose, California. For now, he says, "nanotechnology doesn't exist."

Yet even the most hard-headed nanoscientists must admit that their minute world, by whatever name, is on the move. Advances in manipulating nanosized materials have already led to improvements in computer data storage, solar cells, and rechargeable batteries. Computer disk

NANOPROFILES

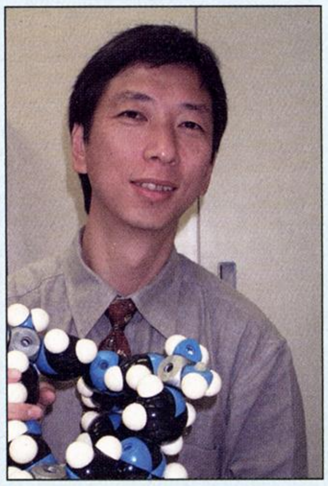
Coaxing Molecular Devices to Build Themselves

NAGOYA—When Nagoya University chemist Makoto Fujita thinks about how to store data in tiny spaces, he thinks big—about how nature handles the problem. Then he tries to emulate the answer. "A living cell is incomparably smaller than a compact disc, but its DNA carries far more information," he says. "Handling data at the DNA's molecular scale could lead to handheld supercomputers. But to do that we need more efficient ways to manipulate molecules."

Fujita and others are doing exactly that through a technique called directed self-assembly. By adroitly exploiting the chemical and electrical bonds that hold natural molecules together, they can get molecules to form desired nanometer-scale structures. This could lead to computer logic and memory devices up to 100 times smaller than their current counterparts. Self-assembled molecules might also serve as cages to hold and deliver unstable medical compounds, and as crucibles for chemical reactions.

The technique builds upon two properties of matter. One is the bonding between hydrogen atoms, which holds the two strands of DNA in its double helix. The other is the electrical attraction between positively charged organic ions and negatively charged metal ions. The organic ions are strategically placed on organic molecules, or ligands, which are like the rods of Tinkertoy sets. The metal ions are like the socketed disks that hold the rods together. Unlike Tinkertoys, however, these metal ions and ligands assemble themselves if mixed together in solution in the right proportions and under the right thermodynamic conditions.

Fujita was among those who pioneered the metal-ion technique in the early 1990s. His first



Spontaneous. Makoto Fujita shows off a self-constructing molecule.

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drives alone—which rely on controlling the thickness of various layers of material on the nanometer scale—account for a multibillion-dollar market. The field's promise has prompted the creation of about a dozen nanotech research centers in U.S. universities alone. The European Community runs several programs in nanotechnology, including the Nano Network, which contains 18 member research centers working in nanomaterials synthesis. Japan, Singapore, China, Australia, Canada, Germany, the United Kingdom, and Russia all support nanotechnology efforts.

And there is more to come. Last month Congress approved the bulk of the Clinton Administration's request for money to launch a new National Nanotechnology Initiative. Next year the initiative will spend some $423 million on nanoscience, with more sure to follow. In Japan, nanotechnology funding is slated to jump 41% next year to $396 million. Several European countries are ramping up efforts as well.

Some U.S. experts hope that the surge in funding will carry over to bolster American research in the physical sciences as a whole. Whereas Congress is 3 years into a 5-year effort to double biomedical research funding at the National Institutes of Health, "support for physical sciences and engineering has been stagnant," says Tom Kalil, a White House specialist on the economics of technology. "We see [nanotechnology] as a way [of] increasing support for physical sciences and engineering."

Richard Smalley, a Nobel Prize–winning chemist, thinks the emerging field may even reverse the long slide in the number of new students choosing careers in science, just as the space race inspired an earlier generation. "It was Sputnik that got me into science," Smalley says. "Of all the impacts of [nanotechnology's rise], the most important impact—and one that I dearly hope will happen—will to be to get more American girls and boys interested in science."

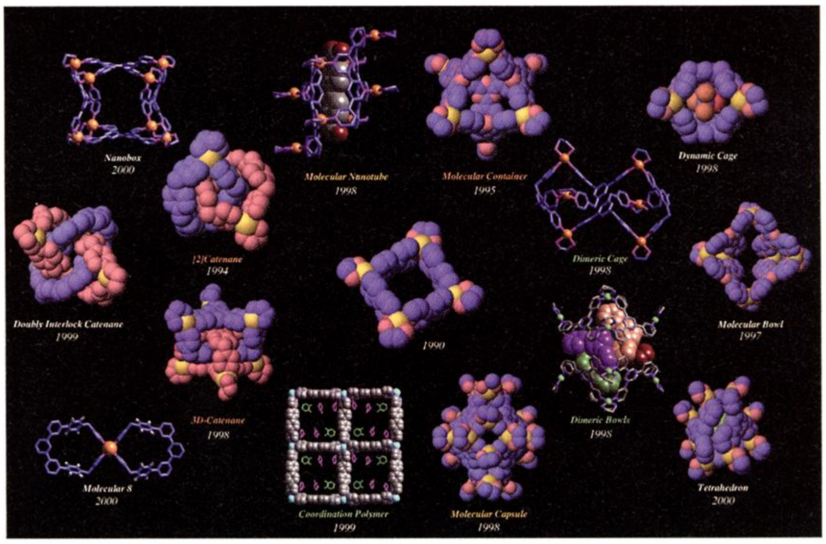
All of this activity is leading to some rather grandiose pronouncements. "This is an area that can have a huge potential payoff that can be as significant as the development of electricity or the transistor," says Kalil. And at a 1998 congressional hearing, Neal Lane, the president's adviser for science and technology and former National Science Foundation (NSF) director, stated, "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."

But however promising nanotech's future may be, transforming it from the world of fiction to reality will mean overcoming some daunting obstacles. Beyond manipulating atoms, nanoscientists must perfect ways to mass-produce nanosized objects and integrate them with the larger, human-scale systems around them. And they must do it while working in an interdisciplinary field that requires new levels of cooperation among different specialties, raising familiar challenges of herding academic cats and coaxing them to march in lockstep.

A new hammer

Of course, nanotechnology—in the guise of nanoscale materials—has already been around for a long time. For the last 100 years, tire companies have reinforced the rubber in car tires by adding nanosized carbon particles, called carbon black. And living organisms from bacteria to beetles rely on nanosized protein-based machines that do everything from whipping flagella to flexing muscles.

Today, the term "nanotechnology" refers most broadly to the use of materials with nanoscale dimensions, a size range from 1 to 100 billionths of



Zoo story. Exotic nanostructures may serve as "molecular cages" or even computers.

construction used four simple linear ligands and four metal ions to produce square macromolecules. More recently, his group has built an eight-sided, three-dimensional structure made up of two pyramids joined at their bases. The molecule is 3 nanometers across, and the cavity is big enough to hold a C_{60} molecule, the so-called buckyball. Fujita and other researchers have also created a variety of grids, tubes, cages, and catenanes, which are rings interlocked like links of a chain. "Such structures cannot be synthesized by conventional chemical reactions, but we can very easily construct them using directed self-assembly," Fujita says.

J. P. Sauvage, a chemist at Louis Pasteur University in Strasbourg, France, has proposed using catenanes as computing devices. One ring would be mechanically fixed, allowing the second ring to rotate. If the second ring has an additional ion, it could be rotated 180 degrees back and forth in response to an adjacent electrical charge. The position of the ring would indicate the 1 and 0 of digital data.

The molecular cages can be constructed to have small openings through which atoms can enter and react with other atoms, forming molecules that are too big to escape. This arrangement, which can capture and stabilize molecules that otherwise rapidly react and disappear if free in solution, could be the basis for a drug-delivery system.

Donald Cram, a Nobel laureate in chemistry who is now retired from the University of California, Los Angeles, used such a cage to capture cyclobutadiene, a compound that briefly appears at intermediate stages of some chemical reactions but which until then had been too unstable for chemists to isolate. Julius Rebek, director of the Skaggs Institute for Chemical Biology of the Scripps Research Institute in La Jolla, California, who works on self-assembly using hydrogen atoms, explains that the characteristics of cyclobutadiene had been theoretically predicted but never confirmed. "By encapsulating the molecule, [Cram kept it] stable long enough to be characterized by nuclear magnetic resonance," he says. Aside from its value to basic research, this trick could be used to deliver drugs that are hard to stabilize.

Fujita predicts that the number of self-assembled molecules and their uses will rise rapidly in the years to come. Whereas a decade ago there were only a handful of groups working on self-assembly using metal ions, he says, "now there are dozens. The field is advancing very rapidly." –DENNIS NORMILE

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