happen, but where does an idea like that come from?

COLWELL: I think it comes from the philosophy that states can do [the program] in block grants. We at NSF know that our approach works very effectively and that it's critical for scientists and engineers who are practicing science and engineering to be the role models in the classrooms.

PT: That seems obvious. So where did the idea to shift the science program to the Department of Education originate?

COLWELL: It's because we have allowed a chasm to develop in transferring what we have learned in the cognitive sciences into the classroom. When you look at transportation in 1900, it was the horse and buggy. In 2004, it's the space shuttle. You look at medicine. If you had diabetes in 1900 you just got treated palliatively and you died early. Now you're talking about almost being close to . . . correcting the insulin-errant metabolism. You look at the classroom in 1900, 1950, and 2004, and it has not changed at the elementary or high-school level. We need to bring the science of learning and understanding into the classroom—along with other obvious things, like having science teachers who majored in science.

PT: You left NSF early, a little short of the full six-year term. Was that because of the opportunity at Canon?

COLWELL: It wasn't early—well, only a few months. I had shepherded the '04 budget through OMB, Congress, and it had been signed by the president. I had negotiated the '05 budget and received White House approval for it. From what I had learned from Congress, we were going to do as well as we could, so it was a good time to leave, on a very good high. And I had accomplished my management objectives. NSF is, as Mitch Daniels said, and I agree with him, the best-managed agency in Washington.

PT: Would you ever return to a government post—say, as director of the Office of Science and Technology Policy?

COLWELL: I will always salute and serve my country. But right now I'm having the time of my life. I hope the community has been happy with my term.

Jim Dawson

Scholars Probe Nanotechnology's Promise and Its Potential Problems

With a revolution in everything from toys to tumors on the horizon, scientists in the nanotechnology arena are working to gain the public's trust.

Hoping to both anticipate pitfalls and head off a publicity fiasco, policymakers and scientists are promoting research and public discussion on environmental, ethical, economic, and other societal implications of the burgeoning field of nanotechnology.

Loosely defined as the purposeful creation of structures 100 nanometers in size or smaller, nanotechnology "is a real revolution because it is changing in a fundamental way how we build things," says Mihail Roco, who chairs the White House subcommittee that coordinates the multiagency National Nanotechnology Initiative (NNI).

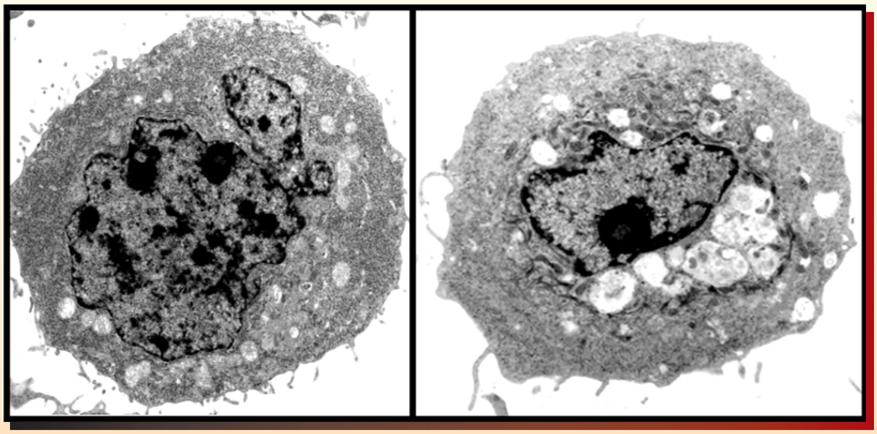
ROY KALTSCHMIDT, LAWRENCE BERKELEY NATIONAL LABORATORY

Students flock to Saturday morning nanotechnology sessions put on by the Molecular Foundry at the University of California, Berkeley.

Scientists predict that applications of nanotechnology will go far beyond their current uses—in sunblock, stain-resistant clothing, and catalysts—to, for example, environmental remediation, power transmission, and disease diagnosis and treatment.

But realizing nanotechnology's potential requires public trust, says Vicki Colvin, director of Rice University's Center for Biological and Environmental Nanotechnology. The human genome project set a good example, she says, with 3–5% of its federal funds earmarked for studying implications of the research. That's in contrast to the nuclear energy and genetically modified organism industries, which are hobbled by bad public relations, she adds. "In GMO, they belittled the concerns of the people, and didn't take the risks seriously. I'd like nanotechnology to be a field that learns from the past."

To that end, some countries are beginning to invest in research into the broader impact of nanotechnology. This year, investment in nanotechnology by governments worldwide exceeds $3.5 billion, Roco says. NNI's fiscal year 2004 budget is $961 million, of which 11% goes to research on health and the environment; additional money is allocated to other studies relating to societal implications. Scholars in the humanities "were very encouraged by the language coming out of the NNI asking for there to be examination of implications early on," says Davis Baird, a philosophy professor and associate director of the University of South Carolina NanoCenter. "Roughly speaking, if you look at a new technology after it's gotten rolling, it's much more expensive to change things. At this stage, if you ask the right questions, you have more chance of nudging the technology in the right direction."



Ultrafine air pollution particles damage mitochondria in cells. Mitochondria, the respiratory and energy transfer engines of cells, appear as small white dots in healthy epithelial cells (left) that were not exposed to air pollution nanoparticles (largely diesel exhaust). The mitochondria in exposed cells (right) are bloated and have black dots in them. (Courtesy of *Environmental Health Perspectives,* where the images, taken by Ning Li and Andre Nel of UCLA, appear in an April 2003 article.)

Magical materials

When matter is manipulated on the atomic scale, optical, electrical, magnetic, and other characteristics of materials change. "It's quantum mechanical in nature, and quantum mechanics is magic," says Stanley Williams, director of quantum science research at Hewlett-Packard Co in Palo Alto, California. "The new properties come out and make themselves available—and a lot of the time they are technologically useful. For example, if you take a hard material, a clay or a ceramic, and powder it down to the nanoscale, and mix it with a polymer, you wind up with a nanocomposite that can have a combination of hardness and toughness never seen in the natural world."

Other features that contribute to nanotechnology's promise are the expectation of cheap, low-polluting mass manufacturing and the possibility of making things, on the scale of biological building blocks, that could imitate or augment living systems. So far, most applications involve enhancements of preexisting materials, but new developments are in the works. A sampling includes lighter, more fuel-efficient cars, iron particles for immobilizing pollutants, and a liquid slurry that, when painted onto a surface, would collect solar energy.

Richard Smalley of Rice University, who won the Nobel Prize in Chemistry for his role in discovering fullerenes, talks about using conducting carbon nanotubes for efficient power transmission, and quantum dots and other nano-sized probes for testing and localizing disease. "We are imagining a time," he says, "maybe in just a decade or two, when the average person can go to a clinic and get a scan that tells the state of health in a noninvasive, low-cost way. This would have tremendous impact." In the more distant future, computers might be connected directly to the brain as a memory aid, he adds. "It would change what it means to be human."

Many questions, few answers

So what are the potential problems associated with nanotechnology? For now, questions far outnumber answers. What are the effects of nanostructures on human health and the environment? Are new protective measures needed to regulate nanotechnology? How do manmade nanomaterials differ from naturally occurring ones? How will individual privacy be protected from surveillance nanosensors? How will inexpensive mass manufacture of nanomaterials change the workforce? How will nanotechnology-related businesses affect local and global economies?

Data are starting to trickle in from studies on health and the environment. For example, nano-sized particles from air pollution have been shown to inflict more damage on cells than do larger particles. And recent results suggest that fullerenes localize in fish brains. "Fullerenes are the poster child of nanotechnology," says Colvin. "We expected them to be inert. They're not." If an industry were to dump fullerenes in a river or sea, she says, "it would probably kill a lot of fish. But we showed there is a simple way to render [fullerenes] nontoxic." Inhalation of engineered nanomaterials is probably not a problem, adds Colvin, "because they exist in small quantities and should have zero vapor pressure. The dermal route may be a bigger issue. I can test whether a particle is toxic and under what conditions. That does not threaten nanotechnology. It makes it more powerful."

The concern that has generated the most attention in the popular press has been gray goo—self-replicating nanobots that could hypothetically get out of control. Such a scenario is widely dismissed by scientists as closer to science fiction than science fact. "No one with half a brain takes that seriously," says Williams. Self-replicating nanomachines can't be made, adds Smalley, whose debate on the matter with Eric Drexler, author of *Engines of Creation: The Coming Era of Nanotechnology* (Anchor Books, 1986), is available at http://pubs.acs.org/cen/coverstory/8148/8148counterpoint.html.

For his part, Drexler, the most visible proponent of what he calls "molec-

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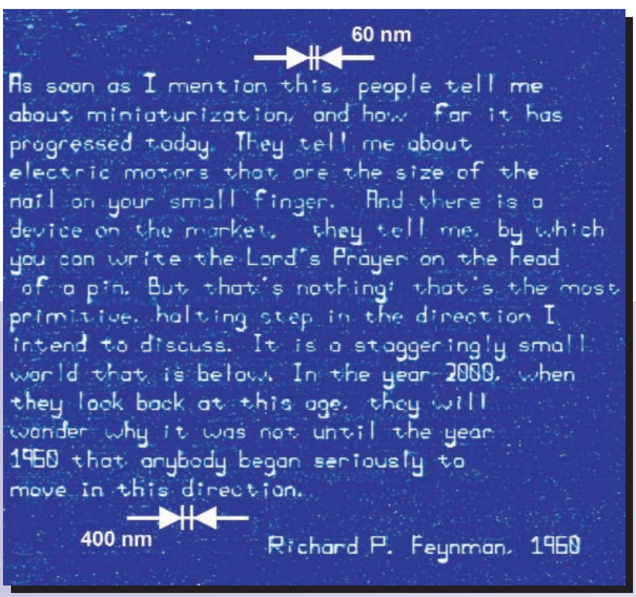

There's plenty of room at the bottom: Some 40 years after Richard Feynman's talk, an excerpt was written in miniature using dip-pen nanolithography.

ular assemblers," maintains that "nanoscale machinery that would be more productive than macromachines and would have the ability to make atomically precise products" can be manufactured. It's "possible but will require the development of new tools" and, he says, would fulfill the vision Richard Feynman famously described in 1959. The term nanotechnology has steered off course to less exciting developments, he adds. "Through the quirks of politics, the mainstream has rejected the original goal. We are raising a generation of researchers who have been told that molecular manufacturing will threaten their careers."

Winning over the public

In any case, gray goo is being considered alongside other potential implications—positive and negative—of nanotechnology in two upcoming studies: a joint report due out this summer by the UK's Royal Society and Royal Academy of Engineering and one next year by the National Academies of Science. Further evidence of the emphasis on the parallel study of nanotechnology and its implications includes a caucus set up in April to keep Congress abreast of developments, NSF's nanotechnology centers' devotion of some funds to study implications, and broadened programs at conferences.

Scaling down*

Human hair (diameter)	60–120 μm
Pollen	10–100 μm
Asbestos fibers (diameter)	<3 μm
Diesel exhaust particles	<100 nm–1 μm
Soot	<10 nm–1 μm
Quantum dots	2–20 nm
Nanotubes (diameter)	~1 nm
Fullerenes	~1 nm
Atoms	1–3 Å

*Approximate ranges

"We want to make sure we don't do anything that is going to cause a backlash," says Williams. "Getting the public against nanotechnology is the biggest danger we face in this field." ETC Group, a technology watchdog organization based in Canada, has called for a moratorium on the use and production of engineered nanoparticles until safety standards have been set and for an international framework for evaluating the economic and social implications of nanotechnology. The UK's Prince Charles has reportedly expressed concern about developments in the field, and here and there people have demonstrated against nanotechnology, as they did at the groundbreaking this past January for the Molecular Foundry, a Department of Energy center at the University of California, Berkeley.

Says Williams, "The risks have been magnified beyond all conceivable realities. Nanoparticles have existed forever. If nanostructures by their very existence were harmful, we wouldn't be here." Still, he adds, "there are potential issues, but we are considering and working them into our research more than has ever been done in the past."

"The biggest problem is often misunderstanding," says Baird. "Go back to C. P. Snow's 1959 essay, 'The Two Cultures.' It argues that the universe is divided into the humanities and the sciences. What I would like to see happen is the building of bridges. How can we engage the public in a way that will be informative, so the public will go away empowered to think about nanotechnology and not be either uncritical boosters or fearful victims?"

Toni Feder