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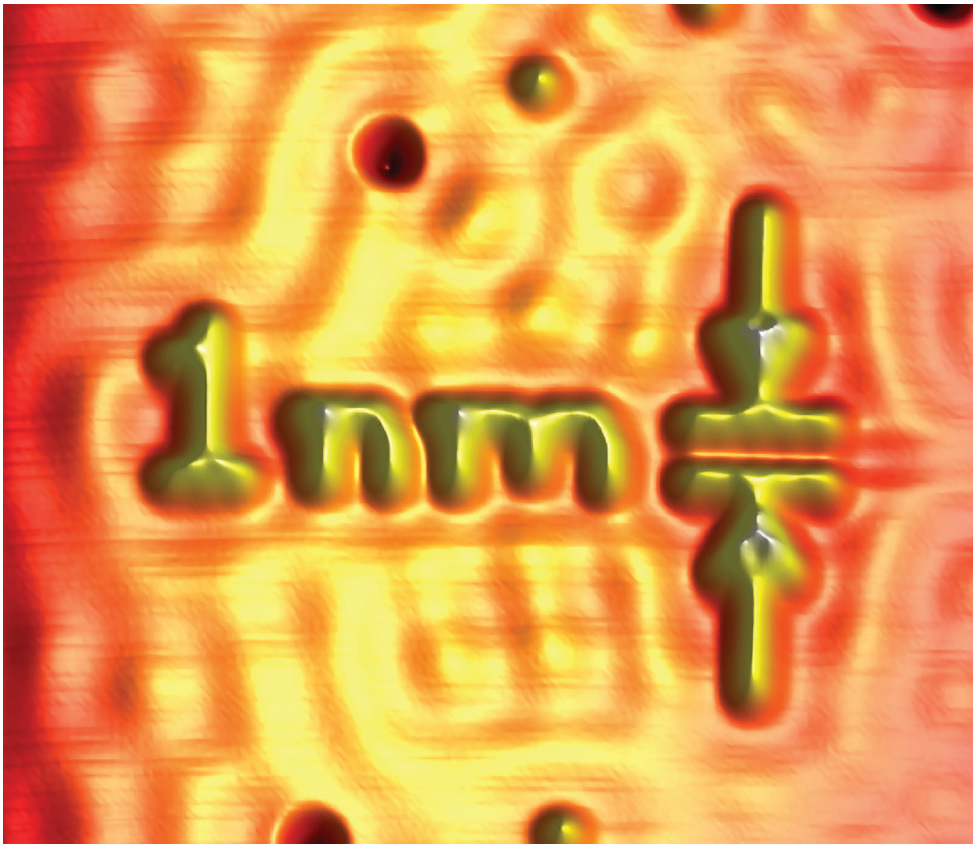

NANOSCALE This scanning tunneling microscope image is made of carbon monoxide molecules on a copper surface. The space between the two arrows is almost exactly 1 nm.

SMALL SCIENCE, BIG FUTURE

Whether nanotechnology will fulfill its promise and transform the world remains to be seen, but scientists have ambitious plans for the field

BETHANY HALFORD, C&EN BOSTON

HARD-CORE PORNOGRAPHY AND NANOTECHNOLOGY don't have much in common. But when it comes to defining what nanotechnology is, the late Supreme Court Justice Potter Stewart's words on the former, "I know it when I see it," seem to resonate with researchers searching for a description of the latter.

Most scientists working in the field, when asked to define nanotechnology, will inevitably turn to the definition given by the National Nanotechnology Initiative (NNI), a program that coordinates federal nanotech research and development. According to NNI, "Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers." Researchers concede that's a pretty broad definition, opening the door to anyone from medical scientists to materials scientists to call what they do nanotechnology.

It wasn't always this way. Initially, nanotechnology had a more specific meaning. Credit for inventing the

word commonly goes to the late Japanese scientist Norio Taniguchi, of Tokyo University of Science. Taniguchi used it in the title of his talk, "On the Basic Concept of 'Nano-Technology,'" at a 1974 engineering conference, where he was speaking about semiconductor processing. Taniguchi's hyphen has long been forgotten.

But a more likely source for popularization of the word is K. Eric Drexler, now a visiting scholar with the Oxford Martin Programme on the Impacts of Future Technology at Oxford University. Drexler used the term in the subheading of his 1986 book "Engines of Creation: The Coming Era of Nanotechnology."

Back then Drexler wasn't talking about the broad research landscape we now see described as nanotechnology. "What I had in mind in my initial publication were nanosystems analogous to what we see in electronics today but with an emphasis on nanoscale devices that could provide ways of making materials and new structures by guiding the motion of molecules," he says.

BUT THE TERM nanotechnology quickly became problematic, Drexler notes in "Nanotechnology: From Feynman to Funding" (*Bull. Sci. Technol. Soc.* 2004, DOI: 10.1177/0270467604263113). Drexler writes that he "chose a word with roots that let it fit any nanoscale technology no matter how old or mundane." Scientists, he adds, were consequently tempted to relabel their nanoscale research as nanotechnology. "During the 1990s it was sort of a running joke," Drexler tells C&EN. "You'd talk about some area of research as 'new and improved—now with atoms.'"

And so Drexler's vision of nanotechnology gave way to the broad field of nanoscale science and technology that today could be summed up as this: Size matters when it comes to matter.

"The general idea that everything when miniaturized is new is an incredibly powerful concept," says Chad A. Mirkin, director of the International Institute for Nanotechnology at Northwestern University and a professor at the school. "If you take any bulk material and you shrink it down to a sub-100-nm-length scale, then you will have a material with new properties—new chemical properties and new physical properties."

The ability to visualize matter on that scale has helped nanotechnology blossom into the field we know today. It's worth noting that Drexler's 1986 publication of "Engines of Creation," which brought nanotechnology into the scientific lexicon, coincided with the invention of advanced microscopy tools, such as the scanning tunneling microscope (invented by IBM researchers Gerd K. Binnig and Heinrich Rohrer in 1981) and the atomic force microscope (also invented by Binnig, along with Calvin Quate and Christoph Gerber in 1986).

These instruments gave scientists the opportunity to peer at atoms, molecules, and larger structures in a way that was previously impossible, says Paul S. Weiss, director of the California NanoSystems Institute and a professor at the University of California, Los Angeles. "Starting with the scanning probe microscopes, our underlying thinking changed," he says. "Now that

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"Nanotechnology is 50% chemistry and 50% instrumentation," Mirkin adds. "You have to be able to see what you make, and you have to be able to manipulate what you make to fully understand it and exploit it."

IN TERMS OF applications, nanotechnology has provided the world with better cell phones, more durable tennis balls, longer-lasting rechargeable batteries, improved medical diagnostics, and smell-fighting socks, to name a few. The Project on Emerging Nanotechnologies at the Woodrow Wilson International Center for Scholars maintains an inventory of consumer products that are enhanced or enabled by nanotechnology. It currently includes more than 1,300 items.

Even so, the world is still waiting for nanotechnology to fulfill its initial promise. "People were all expecting killer applications: big new things, fancy devices, big discoveries that relate to health care. That really hasn't happened," says Jillian M. Buriak, a chemistry professor specializing in nanoscale materials at the University of Alberta. "A lot of that hype came out of simply trying to sell nanotechnology to the public."

"One of my favorite alternate definitions of nanotechnology, which comes from one of our clients, is: 'Nanotechnology is a word you attach to things to attract funding,' " quips Michael Holman, research director at the consulting firm Lux Research.

On a more serious note, Holman says that for companies, nanotechnology has lost much of its mystery in the past decade or so. Back when Lux started up in 2004, he says, "Clients wondered, 'What is nanotechnology? And how is it going to affect my business?' Since then they've understood that nanotechnology is really a broad term for a lot of different technologies that are going to affect a lot of industries and a lot of products in a lot of different ways," Holman says. "If a company is doing cutting-edge science in a lot of areas, then almost inevitably they're doing some nanotechnology."

& VIDEO ONLINE Watch the world's smallest movie, made using a scanning tunneling microscope, at http://cenm.ag/90nano.

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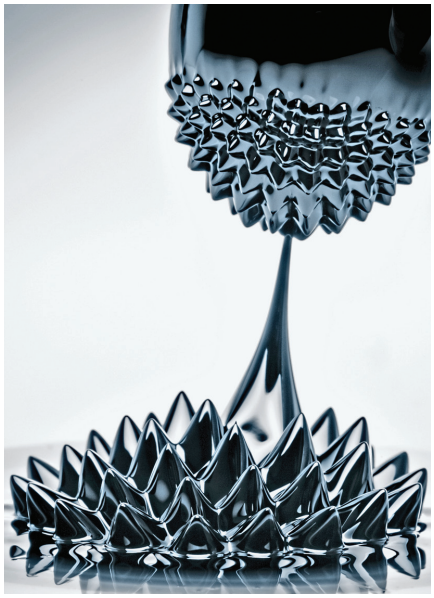
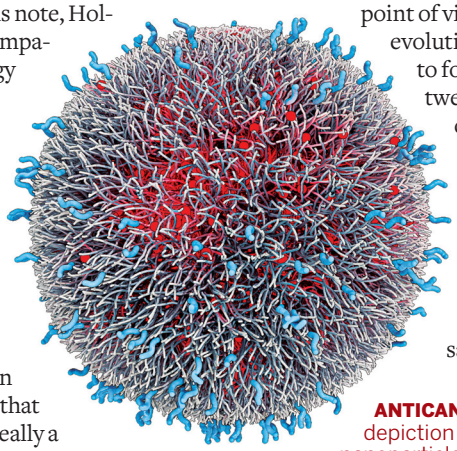


NANOMAGNET A ferrofluid, made up of nanoscale ferromagnetic particles, erupts into spikes in the presence of a magnetic field. Ferrofluids have applications in electronics, such as seals for high-speed computer disc drives.

"The field has evolved painfully slowly and incredibly fast," says Andreas Heinrich, group leader of scanning probe microscopy at IBM, in Almaden, Calif. It's been painfully slow, he says, because the field hasn't lived up to its hype. But from a scientific point of view, nanotechnology's evolution has moved quickly to foster collaboration between scientists in different disciplines. "Breaking down those discipline boundaries is probably the most important thing that nanotechnology or nanoscience has achieved in the scientific world," Heinrich says.



GAËL MCGILL/DIGIZYME

ANTICANCER AGENT An artist's depiction of the cancer-fighting nanoparticle Bind-014. The particle is built from a copolymer (gray) with targeting ligands on its surface (blue) and the chemotherapeutic agent docetaxel (red) encapsulated at its core.

Buriak agrees. "The effect of nanotechnology on science, I think, has actually been far more profound than just a few fancy gadgets and a few isolated breakthroughs," she says. "What nanoscience has done is that it has brought people from all different areas, which previously were very isolated and separated from each other, together. That's where the most interesting science is, and that's where the hardest problems are, at the interfaces between traditional disciplines. That's where you really tackle the big problems that can have a real impact."

"One could see a correlation between the rise of nanotechnology and the dramatically different way we teach chemistry," says James M. Tour, an organic chemistry professor working in nanotechnology at Rice University. "When I got my degree 30 years ago, we worked in one specific area, and we never collaborated with another group," he says. Now students pursue a broader range of subjects and techniques. And Tour says he's just as likely to see students trained in engineering or materials science apply as postdocs in his lab as he is to see organic chemists do so.

DESPITE THE TALK of nanotechnology spurring multidisciplinary research, not all scientists have rushed into the fold, and the science of small things has faced the inevitable backlash. The hype surrounding nanotechnology has naturally led to some cynicism among scientists, but there has also been opposition from those outside the scientific community.

On the silly end of the spectrum, in 2005 a group known as Topless Humans Organized for Natural Genetics, or THONG, engaged in a near-naked protest outside of an Eddie Bauer store in Chicago. Their goal was to bring attention to nanotechnology, which they described as a radical and unpredictable new technology, specifically as it related to Eddie Bauer's stain-resistant clothing made with specially coated fabric from Nano-Tex.

More alarming, in 2011 three so-called ecoterrorists in Europe, from a group calling itself the "ELF Switzerland Earth Liberation Front," were caught trying to bomb an IBM nanotechnology facility in Switzerland while it was under construction. That same year, a group in Mexico, known as Individualidades Tendiendo a lo Salvaje,

or, roughly translated, Individuals Tending to Savagery, sent letter bombs to nanotechnology researchers in that country. Several people were injured in the attacks.

The ecoterrorist fringe and the nanoscientists do have one thing in common: Both see big things happening with the small science of nanotechnology. The former fear environmental disaster and sci-fi scenarios, such as nanobots run amok. The latter say that major advances in health care, materials, and energy made possible with nanotechnology are here already or on the horizon.

"Ultimately, nanotechnology will be something that encompasses a large part of our world," says Paula T. Hammond, an engineering professor specializing in nanotechnology at Massachusetts Institute of Technology. Nanotechnology, she says, will be ubiquitous—in the same way that computers or plastics have touched our lives, nanotechnology will transform the way we do things.

"I think we're still at a very rudimentary place right now," adds Joseph M. DeSimone, a nanotechnology expert at the University of North Carolina, Chapel Hill, and North Carolina State University. "If you look at developments from the early days of nanotechnology, you might think they're not really enduring. But I think you see a new wave coming, where engineering has infused itself into nanotechnology. With engineering comes control and the ability to manufacture and fabricate. With that, you are really going to change people's lives." ■

From C&EN Archives

C&EN has served up a steady diet of nanotechnology-related research fare over the past two decades. But the piece that helped the magazine make its mark in the nanotechnology arena is the 2003 Point-Counterpoint debate between K. Eric Drexler and the late Richard E. Smalley, a professor at Rice University and a Nobel Laureate in chemistry (C&EN, Dec. 1, 2003, page 37). In the piece, two nanotech advocates square off about molecular assemblers—devices capable of precisely positioning atoms and molecules.

Scientists tend to be circumspect, even when speaking on topics about which they hold strong opinions. That was not the case in the Drexler-Smalley debate. Their exchange includes memorable zingers, such as, "Your misdirected arguments have needlessly confused public discussion of genuine long-term security concerns. If you value the accuracy of information used in decisions of importance to national and global security, I urge you to seek some way to help set the record straight," from Drexler to Smalley. And, "I see you have now walked out of the room where I had led you to talk about real chemistry, and you are now back in your mechanical world. I am sorry we have ended up like this. For a moment I thought we were making progress," from Smalley back to Drexler.

Looking back on the Point-Counterpoint article 10 years on, Drexler says the exchange was valuable. "It provided an opportunity to push back on some of the misconceptions that had been in circulation, which I think ultimately come from popular culture and science fiction," he tells C&EN.

"It's part of a growth process for any field—to have some ideas that are maybe a little off the edge and then to have a debate about what's really going on," says A. Paul Alivisatos, director of the Lawrence Berkeley National Laboratory and a nanotechnology specialist at the University of California, Berkeley. Over time, he says, science shows what is possible and what is fiction.

Paula T. Hammond, a nanotechnology expert at Massachusetts Institute of Technology, says the debate helped spark excitement among the public about the science. "Without the public's excitement we would not be able to fund the incredible things that are happening now in the field," she says.

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