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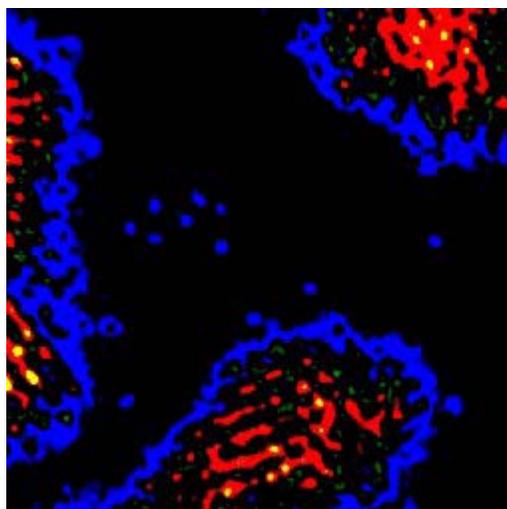
Microscopy Approaches Fundamental Limits

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If God can't pin down tiny atoms, what hope do mere mortals have?

by Alex Stone

The worst primary-school scolding I ever received was for ridiculing a classmate who asked, "What's an atom?" To my third-grader's mind, the question betrayed a level of ignorance more befitting a preschooler, but the teacher disagreed and banned me from recess for a week. I had forgotten the incident until a few years ago, while sitting in on a quantum mechanics class taught by a Nobel Prize-winning physicist. Midway through a brutally abstract lecture on the hydrogen atom, a plucky sophomore raised his hand and asked the very same question. To the astonishment of all, our speaker fell silent. He stared out the window for what seemed like an eternity before answering, "I don't know."



Above and Left, Silicon atoms

measuring four-billionths of an inch across

Image courtesy of S.J. Pennycook, A.R. Lupini, G.M. Veith, Oak Ridge National Laboratory

He was half joking—but only half. He knew the answer was freighted with uncertainty. What is an atom, really, or the particles (electrons, quarks) that compose it? Two and a half millennia ago, the ancient Greek philosopher Democritus imagined slicing bread into ever-smaller pieces, down to irreducible specks, and the [concept of the atom](#) was born. Today the fact that atoms are the building blocks of matter—there are 10^{80} in the universe, 10^{28} of which are inside you right now—is as fundamental to physics as DNA is to biology. No less an authority than Richard Feynman, the modern demigod of quantum theory, defends the primacy of this view in his *Lectures on Physics*. By way of introduction he wrote:

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is . . . that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

Feynman was trying not to scare off his freshmen. In truth, it takes a spectacular amount of imagination and thinking to grasp the sublime elasticity of the atomic domain. Ultimately, as Feynman and his colleagues famously noted, no one ever completely does grasp it.

That is because, on some basic level, atoms and [all subatomic things are invisible](#)—not just in the trivial sense that they are too small to see but also in that, according to quantum physics, they do not have a well-defined position. Worse still, the very act of observing atoms disturbs their state, blurring the image. When physicists speak of uncertainty, it is not flaws in our equipment to which they are referring but to an innate ambiguity that our best efforts cannot eliminate, even in principle. It is impossible to measure, say, the angular momentum of an atom in more than one direction, not because of any experimental challenges involved but because, as Reed College physicist David Griffiths is fond of saying, “God doesn’t know.” If God can’t get a fix on atoms, then what hope do mere mortals have?

Well, physicists are a stubborn bunch. In the late 1960s, after about half a century of trying, they finally got their first real look at atoms. Researchers used a new tool—scanning transmission [electron microscopy](#), or STEM, in which a beam of electrons plays the role that a beam of light normally does. By beaming high-voltage electrons through a sample and recording how the electrons scatter off the nuclei, STEM builds up a picture point by point.

The first person to see an atom was Joe Wall, a graduate student at the University of Chicago in 1969. He worked in the physics lab of Albert Crewe, who developed the earliest STEM with truly atomic-scale resolution. Crewe’s team was trying to image an atom of uranium, a large element with 238 protons and neutrons, number 92 on the periodic table. When they succeeded, it was cause for celebration. “Crewe had a couple of bottles of champagne in the fridge, and he pulled them out,” Wall remembers.

Since then, STEM imaging technology has advanced at a rate not seen since the 1930s, when the resolution of optical microscopes doubled almost every year. Breakthroughs in microfabrication, electromagnetic optics, as well as in high-speed computers that can adjust for aberrations and analyze images, have so improved accuracy that STEM imaging is now approaching the fundamental limits of vision set by quantum mechanics.

The current world record is held by the Electron Microscopy Group at Oak Ridge National Laboratory, where STEM images have been produced with a resolution in the range of 0.6 angstrom—less than one-millionth the width of a human hair. A typical atom is about one angstrom wide, and Crewe’s lab had managed to see only down to a little under three angstroms. “We can now see all these atomic details with a clarity we’ve never had before,” says the Oak Ridge group’s leader, Stephen Pennycook. “It’s like being blind and putting on your glasses and being able to see.”

Being able to see how atoms and bonds are organized in different types of matter is allowing scientists to design better materials. “The *Titanic* didn’t sink because it hit an iceberg; it sank because the steel was brittle and it cracked,” Pennycook says. “If you know the structure of a material, you can figure out how to improve it.” The understanding gleaned from STEM images has led to major improvements in the design and fabrication of computer chips.

Currently, the smallest atom scientists can see is lithium, number 3 on the periodic table. The next milestone is to push the resolution below the Bohr radius, about half an angstrom. At that level, even the tiniest atoms—hydrogen and helium—come into view. “That may take a couple of years,” Pennycook says. The ultimate dream is to take STEM into three dimensions with confocal electron microscopy, which images a material in slices by changing the focus of the beam. Pennycook and others have made major strides in this direction, and 3-D pictures of individual atoms are already becoming available. “This is a historic time,” says Pennycook. “Only once do we pass that threshold of being able to see atoms.”

Yet physicists know they are also approaching a wall. “We’re getting close to the fundamental limit due to quantum zero energy,” Pennycook notes. In quantum mechanics, every particle is a little blurry because it always carries a minimum iota of energy—the so-called ground state energy. Cooling the sample to ultralow temperatures helps [slow the atoms down](#), but they will never sit perfectly still for the camera. “You can cool the atom, but you’ll never stop it entirely,” Pennycook says. Physicists expect STEM to bottom out at around one-tenth of an angstrom. No matter how much our technology improves, on some level atoms will always remain invisible.

Beyond the STEM image lies only the imagination. In poet Muriel Rukeyser’s words, “The universe is made of stories, not of atoms.” Physicists have laid bare the atomic domain, and what we will never see is as meaningful—and beautiful—as what we can.