FULLERENES

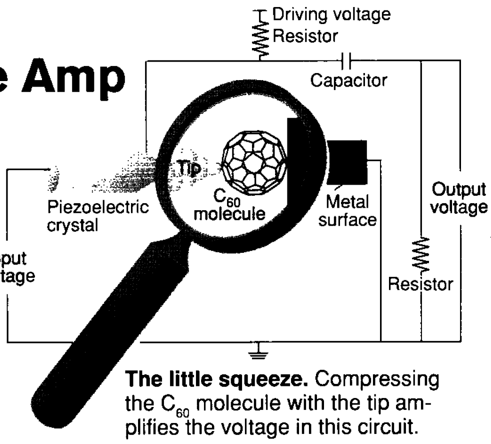
Trapped Buckyball Turns Up the Amp

In the dozen years since their discovery in 1985, the soccer-ball–shaped molecules of 60 or more carbon atoms now known as fullerenes have displayed a dazzling variety of tricks. Although real-world applications are still a way off, researchers have coaxed these "buckyballs" to become superconductors at low temperatures, emit light and carbon ion beams, and form many other compounds with different properties. Now, two European researchers have added something new to this list of talents: They have created an electromechanical amplifier from a single buckyball. "Nothing like this has been done before, and the experimental know-how to be able to do this is highly impressive," says Daniel Colbert of the Center for Nanoscale Science and Technology at Rice University in Houston.

This demonstration came about through a piece of serendipity. In 1995, Christophe Joachim of the CNRS Laboratory for the Study of Materials and Structures in Toulouse, France, and James Gimzewski at the IBM Research Laboratory near Zurich, Switzerland, tried to measure the electrical resistance of the basic fullerene molecule, C_{60}, using a scanning tunneling microscope (STM). This instrument can map out details of a surface with atomic accuracy by passing a current from an ultrafine tip to the surface and detecting changes in the current when the tip scans over it. The researchers used the STM tip to hold down a single C_{60} molecule on a metallic surface so they could measure the current through it. But they noticed, to their surprise, that the apparent resistance of the molecule changed drastically when they squeezed and deformed it with the STM tip. "We found this funny," says Joachim. "Why shouldn't we try to use it as an amplifier? we wondered."

So the team constructed a simple circuit based around the STM to demonstrate C_{60}'s ability to amplify an electrical signal. The key to the setup is the piezoelectric crystal that controls the distance of the STM tip from the surface. Such a crystal expands when a voltage is put across it. One loop of the circuit controls the voltage to the crystal, while a second loop passes a current down through the tip and the C_{60} molecule to the metal surface. Upping the voltage in the crystal circuit by 20 millivolts expands the crystal and moves the tip 1 angstrom (10^{-10} meters) closer to the surface, compressing the buckyball by about 15%. The resulting resistance change in the buckyball changes the voltage in its circuit by 100 millivolts. Hence, the input voltage to the crystal has been amplified by a factor of 5.

The researchers are now investigating other molecules in search of the same properties. "Perhaps we can expect a similar effect when you deform a nanotube; to my knowledge, nobody has tried this yet," says Gimzewski. They are also looking for other ways to compress the molecule. Possibilities include tiny actuators similar to the bimetallic strips used in thermostats, or molecules that deform in response to light, an effect known as photochromism. "The active element can consist of just one molecule," says Gimzewski.



The little squeeze. Compressing the C_{60} molecule with the tip amplifies the voltage in this circuit.

SOURCE: CNRS

Gimzewski's most recent work takes a step in this direction: He and his team have created a monolayer of bianthrone molecules on a copper substrate. These molecules change shape when irradiated by light. The team then attached C_{60} molecules to that layer and repositioned these molecules using an STM tip without destroying the monolayer—demonstrating for the first time that it is possible to move buckyballs around on top of a molecular monolayer. "Our research is now moving toward supramolecular systems, and this is one example of such a system—one type of molecule interacting with another type of molecule," says Gimzewski.

Practical applications are still far off, but "in a number of years, conventional microelectronics could run out of steam, and it is important to start now to look at possibilities from other directions," says Gimzewski. Colbert agrees: "The import is as a demonstration of things to come. We are going to look back in 5 or 10 years and consider these things as important demonstrations of our beginning to play in this playground."

–Alexander Hellemans

Alexander Hellemans is a science writer in Paris.

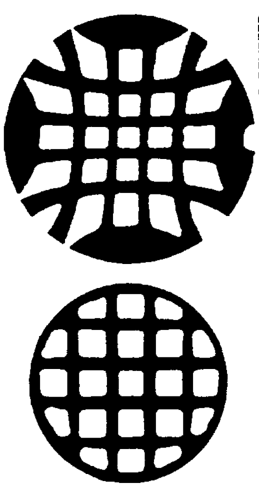
ELECTRON MICROSCOPES

Electron Mirror Gives a Clearer View

Optics researchers since Newton have known that any lens, no matter how well ground, suffers from flaws that will blur an image and add a rainbow fringe to its edges. Even the lenses in electron microscopes, which use beams of electrons instead of light to create images, can't escape these kinds of aberrations. Researchers long ago came up with corrective measures for light-focusing lenses. Now, a fix is in sight for electron microscopes as well, an Oregon team reports in the current issue of *Microscopy and Microanalysis*.

The fix—a corrective mirror developed by physicist Gertrude Rempfer and her colleagues at Portland State University—could increase the resolution of some high-powered electron microscopes by a factor of 5 or more. That's potentially enough to distinguish receptors on a cell membrane. "It's a technological tour de force," comments Jon Orloff, who works on electron optics at the University of Maryland.

It has been more than 250 years since Englishman Chester Moor Hall learned how to correct for the foibles of glass lenses. Glass brings different wavelengths of light, or colors, to focus at slightly different points, creating a blur of colors called chromatic aberration. Even light of just one wavelength won't focus perfectly, because rays passing through the edges of a lens bend too much, in what is known as spherical aberration. In 1732, Hall hit on the idea of passing the light through another lens that had the opposite defects and canceled out the aberrations.



G. REMPFER

Looking sharp. An electron image of the same screen, with *(bottom)* and without correction.

Rempfer and her colleagues looked for a similar solution to the aberrations introduced by the lens of an electron microscope, which consists of metal plates or magnetic or electric fields. Like a glass lens focusing light, electron lenses refract electrons of different energies by different amounts, causing the equivalent of chromatic aberration, and they suffer from a kind of spherical aberration as well. The Oregon team's solution is to send their beam of electrons into an electron "mirror," consisting of a hyperbolic electric field that bends the paths of the electrons even as it repels them.

Because higher energy electrons penetrate deeper into the electron mirror before they are reflected, the field has more time to bend their paths, introducing a pattern of aberrations that exactly cancels those introduced at the lens.

"This is the answer to a problem that has plagued electron microscopy for the past half-century," says University of Wisconsin physicist Brian Tonner. While it could ultimately benefit the two most common kinds of electron microscopes—scanning and transmission—its most immediate application will be for so-called photoelectron emission microscopes (PEEMs), says O. Hayes Griffith, a physical chemist at the University of Oregon, who collaborated with Rempfer.

A PEEM bombards surfaces with intense visible or ultraviolet light to spur the emission of electrons, then focuses the electrons into an image. The emitted electrons come in a wide range of energies, however, resulting in strong chromatic aberration. One solution has been to restrict the wavelength of light, eliciting electrons at just a single energy—but also producing a dim image. By eliminating the aberrations with the mirror, "you could make a bright, quick picture without losing resolution," says Martin Kordesch, a physicist and electron microscopist at Ohio University. The mirror could also increase the ultimate resolution of these microscopes from 70 angstroms to 10 or fewer, roughly the scale of atoms, says Griffith.

Surface scientists, who study the composition and chemical behavior of surfaces, would be the most immediate beneficiaries. But the corrected optics could also aid biologists. For example, researchers examining receptors on a cell surface now have to label them with fluorescent markers. "That's like seeing the headlights of a car far away," says Griffith. With a corrected PEEM, "you could see membranes right down to the cellular proteins, like looking at a landscape in daylight."

That's still in the future, though. The Oregon group has not yet attached their mirror to a working electron microscope. Meanwhile, Tonner's research group at the Wisconsin Synchrotron Radiation Center is trying to build a prototype corrected PEEM, and in Europe, a consortium of German groups has mounted a multimillion-dollar effort to build a corrected microscope. But in the race for higher resolution, says Tonner, Rempfer and her electron mirror have "made a quantum leap."

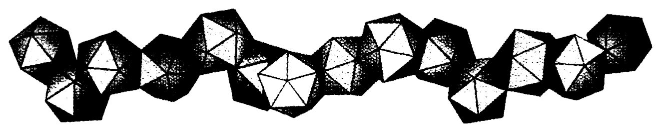
–Erik Stokstad

MATHEMATICS

How to Play Platonic Billiards

SAN DIEGO—Billiards is a game of geometry. Expert players delight in setting up incredible "trick" shots based on careful calculation of angles and distance. Now, Matthew Hudelson has added a new dimension to this pastime, as he reported here last month at the joint meetings of the American Mathematical Society and the Mathematical Association of America. With a little help from a computer, the Washington State University mathematician has demonstrated some amazing three-dimensional shots for a cue ball bouncing around inside three equal-sided, or Platonic, solids—the eight-sided octahedron, 12-sided dodecahedron, and the 20-sided icosahedron. Each of Hudelson's shots hits each side of the pertinent solid and returns to its exact starting point and direction of travel.

That's no trick on a 2D billiard table, provided it has a regular shape. Just start the ball at the midpoint of one side and aim for the midpoint of an adjacent side. But add a dimension and the problem gets far more interesting. When Hudelson took up the challenge, mathematicians had worked out the required trajectories for only the two simplest Platonic solids. Hugo Steinhaus gave the answer for the cube in the 1950s, and John H. Conway and Roger Hayward independently solved the tetrahedron in the early 1960s. Both cases were described in a 1963 *Scientific American* column by Martin Gardner, who says he is "quite impressed" with Hudelson's extension. Conway, now at Princeton University, agrees: "It's a very nice result."



M. HUDELSON

Plumber's nightmare. Part of a chain of icosahedra.

In principle, solving the problem is just a matter of algebraic bookkeeping—tracking the equations of the straight lines the ball follows as it bounces around. A standard theoretical approach is to glue together a sequence of "reflected" copies of the shape or solid at the sides in the order in which you expect they will be hit. If there is indeed a trajectory that hits the sides in the prescribed order, then there will be a straight line that stays inside the glued-together construction, because each time the ball hits a wall, the mirror image of the ricochet is a straight line that continues the incoming shot.

What makes things difficult is the sheer number of possibilities that have to be investigated, particularly for the dodecahedron and icosahedron. Even for the octahedron, there are hundreds of different ways to glue together eight copies of the shape, each corresponding to a different order in which the ball hits the walls. That's a lot of algebra.

Hudelson took up the problem last summer after hearing it mentioned in a geometry seminar at Washington State. He started with the octahedron. First, he fashioned a likely arrangement of stuck-together octahedra made with cardboard and tape. The resulting "plumber's nightmare," as Hudelson calls the tube, told him that there would be trajectories that hit the eight walls in the order he had guessed. It was then a relatively simple exercise in computer algebra to identify one path that returned the ball to its starting point and its original direction of travel.

RHONDA ROLAND SHEARER PHOTO BY: LEE BOLTIN

Anyone for a game? Mathematicians have mastered return shots within five Platonic solids.

For the dodecahedron and icosahedron, Hudelson had the computer do all the work. To get started, he wrote a program that generated random initial trajectories and followed them for the first 12 or 20 bounces. Running the program 100,000 times for each solid, he got about 50 trajectories that hit all 12 sides in the dodecahedron and about five that hit all 20 sides in the icosahedron. Each of the successful trajectories hit the walls in the same order, which suggested that there is essentially only one solution to the problem for each solid. He then went on to identify the one trajectory that took the ball back to its starting point and direction.

Hudelson doesn't see immediate applications for these virtuoso shots: "It just seemed like a hole that needed filling." However, he notes that theoretical physicists, who use billiards on odd-shaped tables as a model of the behavior of atoms jumping chaotically between energy states, may turn out to be avid players (*Science*, 20 December 1996, p. 2014). If and when physicists make the leap from two to three dimensions, Hudelson's Platonic shots will be ready to show them a trick or two.

–Barry Cipra