cyber clones oscillate spontaneously and with considerable stochastic fluctuation. As figure 2 shows, turning on the coupling brings the spontaneous oscillations into phase and mitigates the stochastic fluctuations.

In principle, coupling can account for the cochlear amplifier in mammals, whose ears are more complex than those of the bullfrog and other lower vertebrates. Mammals have two kinds of hair cell, inner and outer. The outer cells are elastically coupled to each other but not to the inner cells, which convey the auditory signal to the brain. It's likely that the outer cells deliver their amplification signal to the inner cells through the intervening fluid via viscous coupling.

But something else happens in the outer hair cells. Embedded in the membrane of each cell at a density of around 4500 molecules/μm^2 is a rod-shaped protein called prestin. Depending on the voltage across the membrane, the prestin molecules either lie parallel to the membrane surface or bunch together perpendicular to it.

That piezoelectric bunching shortens the cell and provides a second mechanism for converting mechanical energy into electrical energy. At around 1 ms, the membrane's discharge or *RC* time is too long for the voltage-dependent bunching to play a role in amplifying high-frequency hearing, but it could supplement elastic coupling at lower frequencies.

Charles Day

References

1. P. Martin, A. J. Hudspeth, *Proc. Natl. Acad. Sci. USA* **96**, 14306 (1999).
2. K. Dierkes, B. Lindner, F. Jülicher, *Proc. Natl. Acad. Sci. USA* **105**, 18669 (2008).
3. J. Barral, K. Dierkes, B. Lindner, F. Jülicher, P. Martin, *Proc. Natl. Acad. Sci. USA* (in press).

Focus on improving transmission electron microscopes starts to pay off

The latest advance is the chemical identification of closely spaced, lightweight atoms.

Since their invention in the 1930s, transmission electron microscopes (TEMs) have been an invaluable tool, providing highly magnified images of objects that range from biological specimens to electronic materials. Now, researchers are seeking greater performance from those instruments, especially the capability to determine three-dimensional structures with atomic resolution, to chemically identify individual atoms, or to follow the dynamic behavior of atoms within a sample. Of particular interest are materials with low atomic number *Z*. Some researchers are keen to explore materials such as carbon nanotubes, graphene, and boron nitride for novel electronic applications. Others are interested in determining the structures of biological molecules, especially ones that aren't amenable to being crystallized and hence aren't candidates for crystallography.

A worldwide 60-year effort to correct spherical and chromatic aberrations has brought about, in the past decade, TEMs with much better resolution.[1,2] Spherical aberration results when electrons traveling at different distances from the axis of an electron beam are focused differently by magnetic-field "lenses." Chromatic aberration stems from the different focusing of electrons of different energies. Uncorrected TEMs have operated for many years with electron energies of 200 keV and above because the effect of aberrations grows worse for lower-energy electrons.

TEM designers can compensate for spherical aberration by adding magnetic multipoles along the electron-beam path. It sounds simple in principle but is difficult in practice because the correction for one aberration can unleash a horde of parasitic aberrations. Chromatic aberration can be mitigated by reducing the energy spread of the electron source, typically to a few tenths of an eV. But reduction in energy width can decrease the beam intensity and hence degrade the image quality. Another way is to build a corrector that focuses electrons to the same point regardless of energy.

With aberration correction, TEM resolution has been improved by a factor of two to three. The improvement has been greatest at the electron energies below about 80 keV that are required to avoid radiation damage to materials containing low-*Z* atoms. The knock-on damage threshold is set by the energy an electron must have to kick an atom out of its position within a sample; its value is strongly dependent on atomic mass and bonding. Now, even below 80 keV, the new generation of TEMs can resolve interatomic spacings of less than 0.1 nm.

A recent experiment has exploited the high resolution now possible at low energies to identify individual light atoms in a single atomic layer.[3] The showpiece of the work is the experimental image seen in figure 1a, which shows impurity atoms of carbon and oxygen randomly positioned in the regular array of atoms, replacing boron and nitrogen atoms in a BN monolayer. The work, by Ondrej Krivanek and coworkers from the Nion Company in Kirkland, Washington, along with researchers from Oak Ridge National Laboratory, the University of Oxford, and Vanderbilt University, was done on a TEM at Oak Ridge that operated in a scanning mode.

Two types of TEM

In a conventional TEM, a broad electron beam is diffracted by the atoms in a sample. Experimenters record the resulting interference pattern of the transmitted and diffracted electron waves and deduce the atomic structure from the phase contrast in the recorded image. The scanning TEM shown in figure 2 is an alternative design, in which a tightly focused electron beam is scanned across the sample, one small spot at a time. As shown in the figure, an STEM can be equipped with one or more detectors to collect the electrons transmitted from each spot: An annular dark-field (ADF) detector and an electron-energy-loss spectrometer (EELS).

Each type of TEM has its advantages. A conventional TEM images a wide area of the sample in a shorter time and hence lends itself better to studying dynamic changes. An STEM equipped with either an ADF detector or EELS can provide direct information about individual atoms.

A number of companies and research centers have focused on advanced TEM development. One is Nion, founded by Krivanek and Niklas Dellby in 1997. The US Department of Energy has spearheaded an effort called TEAM to develop ultrahigh-resolution TEMs. TEAM is led by Lawrence Berkeley National Laboratory's National Center for Electron Microscopy and includes FEI Co of Oregon and the Netherlands as well as Corrected Electron Optical Systems GmbH of Germany. In Germany, a TEM development program called SALVE is headed by Ulm University, with the participation of CEOS and Carl Zeiss GmbH. Others involved in TEM development are JEOL Ltd and Hitachi Ltd in Tokyo.

Which atom is which?

To test the ability of the ultrahigh-resolution TEMs to discriminate between atoms, researchers have turned to imaging BN monolayers, structural cousins to graphene sheets. They're a good choice for such a test because they contain two elements in a well-defined chemical structure. In the past year, three groups have produced atomic-resolution TEM images of thin BN layers and studied those structures.[4–6] The observed difference in phase contrast between B and N atoms was very small. The only way to discriminate between the two atom types was to combine multiple images and impose prior knowledge of the hexagonal BN lattice.[5–6]

To provide a more direct identification of the B and N atoms, Krivanek and his group used an STEM with 0.1 nm resolution at 60 keV. The instrument was equipped with an annular dark-field detector, which was first developed in the 1970s by Albert Crewe and his colleagues. The ADF detector is a scintillation counter that surrounds the scattered beam and, in the instrument used by Krivanek's team, collects electrons scattered at half angles ranging from 58 to 200 mrad. The only electrons likely to be scattered to such angles are those undergoing Rutherford scattering with the partially screened atomic nuclei. The scattering intensity increases with Z^{α}, where α is around 1.7.

Researchers have used STEMs with ADF detectors in the past to identify heavy elements such as uranium and gold. They have, for example, identified high-Z dopants at grain boundaries and in semiconductors. It was not clear, however, whether the signal from lighter atoms would be strong enough to distinguish them from one another. Krivanek's team showed that it can be.

In a plot of the raw data, the hexagonal pattern of B and N atoms is discernable, but researchers can't directly interpret the deviations from the pattern to find out which impurity atom sits where. That's because the tail of the electron probe centered on one atomic site adds to the scattering from the nearest neighbor sites. Krivanek and his colleagues removed the probe-tail contributions computationally and smoothed out the statistical noise to generate the black-and-white portion of the image in figure 1a. Superposed on it are colored atoms from a density-functional-theory simulation of a BN monolayer with C and O impurities. The C atoms substitute in pairs for B-N pairs and not for individual B or N atoms, whereas single O atoms substitute only for N atoms. The bright spot on the left edge is a higher-Z impurity.

The histogram in figure 1b plots the number of pixels where the intensity, after subtraction of the tails, had a particular value. It reveals four clearly separated peaks. Contributions to the first and third peaks come from the respective positions that B and N atoms occupy

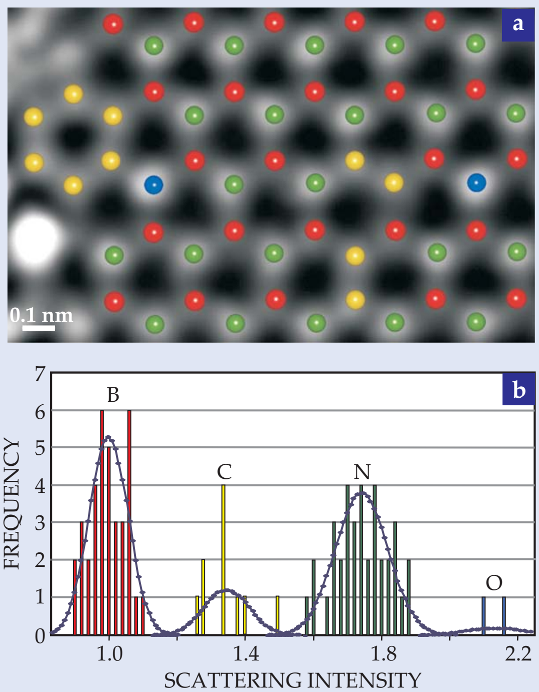


Figure 1. Atoms identified in a boron nitride monolayer. **(a)** A smoothed black-and-white experimental image reveals bright spots of different intensities. Superposed on the image is a model showing atoms whose atomic numbers and positions correspond to the intensities. Boron (red) and nitrogen (green) atoms constitute the regular BN lattice; carbon (yellow) and oxygen (blue) atoms are substitutional defects. **(b)** Histogram of measured intensities (normalized to the height of the lowest-intensity peak) shows a clean separation between atoms with different atomic numbers. (Adapted from ref. 1.)

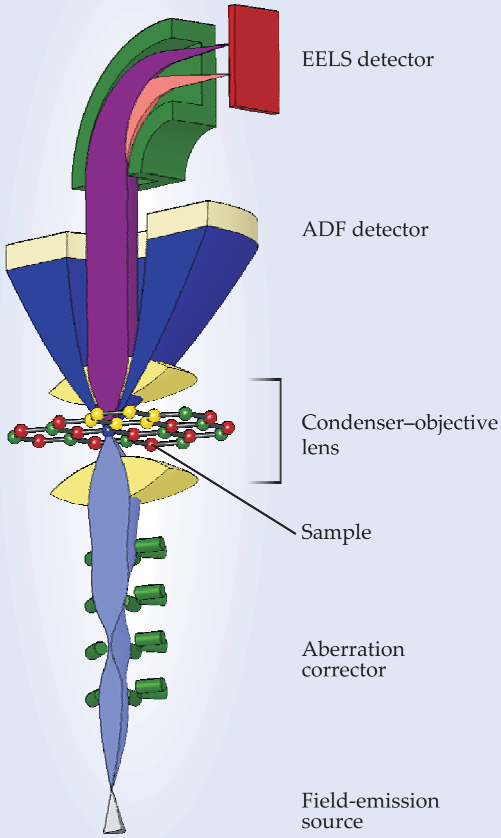


Figure 2. Schematic of a scanning transmission electron microscope equipped with two types of detectors. Electrons emerging from the field–emission source pass through an aberration corrector and are then focused by the first half of the microscope's main lens (the condenser-objective lens) and scanned over the sample. Transmitted electrons pass through the second half of that lens onto one of the two detectors: The electron-energy-loss spectrometer (EELS) measures the energy loss of the forward-scattered electrons. The annular dark-field (ADF) detector is a scintillator that monitors the intensity of electrons scattered at wide angles. (Courtesy of Ondrej Krivanek and George Corbin, Nion Co.)

in the BN lattice. The other two peaks appear to come from C and O impurities. Indeed, when experimenters assume that the average intensity of each of the four peaks corresponds, in increasing value, to atomic numbers of $Z = 5, 6, 7$, and 8, respectively, a curve of intensity versus Z is consistent with the theoretically expected power-law dependence.

Krivanek identified two key components that produced those results: One was the high resolution that resulted from introducing a spherical aberration corrector as well as using a cold field-emission gun with a high electron current and a small energy spread (0.3 eV). The second was the extreme stability of the microscope. The key parts of the 2.7-meter-tall instrument do not move more than 0.01 nm with respect to each other. Krivanek and his team also had very stable computer-controlled power supplies for the many optical elements that can deflect the electron beam. They put as much effort into achieving that level of mechanical stability as they did into the aberration correction.

The presence of the C and O impurity atoms was serendipitous, Krivanek says. He and his coworkers set out to demonstrate element identification on a BN monolayer. Even though they operated well below the knock-on damage threshold, some damage mechanism caused holes to open in the BN lattice in one of their many samples. Those holes were quickly filled by C and O impurity atoms, whose presence enhanced the experimental demonstration of element identification.

"This work is remarkable for the image resolution it achieves at 60 keV," comments Jian-Min Zuo of the University of Illinois, Urbana-Champaign. Although other groups have obtained similar resolution at slightly higher voltages, the advantage in identifying atoms came from combining an STEM with an ADF detector.

The next steps

Kazu Suenaga of the National Institute of Advanced Industrial Science and Technology in Tsukuba, Japan, whose group performed one of last year's TEM studies of BN monolayers, agrees that the work of Krivanek's team represents great progress. Still, he adds, neither ADF nor TEM imaging is really element selective. To discriminate between atoms unambiguously, he feels, one should use spectroscopic techniques such as EELS.

Some of the electrons monitored by EELS will lose energy during inelastic collisions that excite an electron from the inner shell of an atom to an unoccupied state. The energy difference provides a distinct signature of each particular element. Both Suenaga's group and Krivanek's team have reported using EELS to study nanotubes that contain nanopods filled with single atoms such as erbium.[7,8]

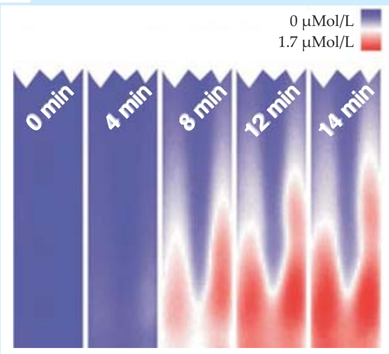
Electromechanical probes such as scanning tunneling microscopes (STMs) and atomic force microscopes (AFMs) are alternative instruments for imaging molecules on a surface, but unlike TEMs, they cannot say anything about deeper layers. Alex Zettl of the University of California at Berkeley is interested in the exotic combination of manipulators like STMs and AFMs and detectors like TEMs. When embedded in a TEM, an STM or AFM can manipulate objects on a surface as the TEM dynamically images the resulting changes. Such manipulators have been embedded in the older generation of TEMs.[9] Zettl is among those working to incorporate them in the new generation of TEMs. The bottom line, says Zettl, is that "technology advances are opening many new doors."

Barbara Goss Levi

physics update

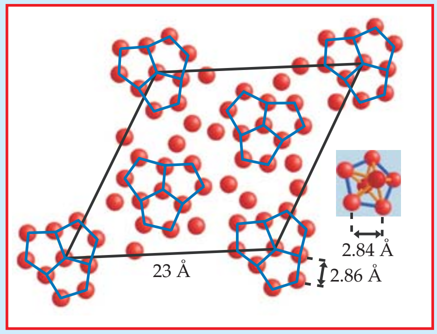
These items, with supplementary material, first appeared at http://www.physicstoday.org.

Replicating and trapping DNA. In living organisms, the complex directional capabilities of cell membranes ensure the concentration and confinement of DNA and the ingredients needed for its replication. But how was that accomplished at the dawn of life on Earth, when there were no such membranes to constrain indiscriminate diffusion and entropy growth? At the University of Munich, Dieter Braun's biophysics group has addressed those questions with a suggestive demonstration of efficient DNA replication and accumulation driven only by a quasistatic thermal gradient in a fluid-filled glass capillary stocked with nucleotides, a polymerizing enzyme, and a small initial template charge of a DNA with 143 base pairs. The 0.1-mm-wide capillary is meant to mimic pores at hydrothermal vents in early seas. The thermal gradient is provided by an IR laser. The gradient drives DNA molecules away from hot spots and sustains a convective flow that subjects the DNA to thermal cycles that create new DNA and concentrate it at the sealed ends of the capillary. The convective cycles promote unraveling of the double helix at 86 °C and its subsequent replication at 60 °C. The DNA population doubles every minute or so, until the closed system's exhausted nucleotide reserve eventually puts an end to that exponential growth. The figure shows the growing DNA concentration at one of the capillary ends over a span of 14 minutes. With continual nucleotide replenishment, such a system might replicate DNA at the rate of 1700 doublings per day. So aside from its possible relevance to paleobiology, the result is of biotechnological interest. (C. B. Mast, D. Braun, *Phys. Rev. Lett.* **104**, 188102, 2010.)



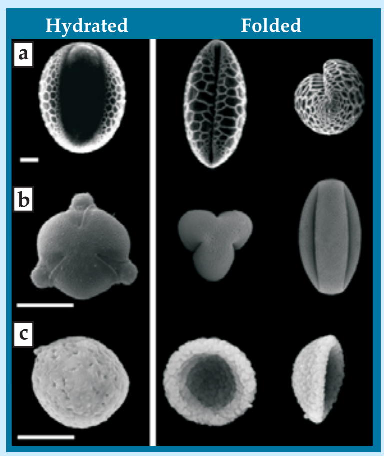
—BMS

Delayed freezing in a supercooled liquid metal. In the presence of a suitable nucleating agent, a liquid in a metastable state below its thermodynamically defined melting point freezes. That's what happens when atmospheric aerosol particles in clouds cause supercooled water droplets to form snowflakes. Researchers have suspected that the atomic surface structure of the seeding particles acts as a template, inducing local order in the disordered liquid and catalyzing its crystallization. Conversely, a solid with a different structure can inhibit crystallization, as has now been observed at the European Synchrotron Radiation Facility in Grenoble, France, by Tobias Schülli and his colleagues. The researchers coupled x-ray scattering data with molecular-dynamics simulations to study supercooled gold–silicon droplets on a silicon substrate, a system that is used to grow Si nanowires. Surprising results emerged when they heated the AuSi alloy above 676 K: As it cooled, the Si atoms leached onto the substrate and, as the figure shows, rearranged its surface atoms into pentagonal clusters. The alloy's atoms near the interface mimicked the substrate's surface structure (see inset), but the resulting local order did not promote crystallization in the droplets, which froze at 513 K, about 120 K below the freezing temperature for the AuSi alloy. Apparently, the pentagonal geometry inhibits freezing because it is not conducive to crystal packing. That finding suggests that substrates with such atomic structures offer a simpler method of maintaining and observing the supercooling process than techniques like magnetically levitating or otherwise suspending the liquid droplet. (T. Schülli et al., *Nature* **464**, 1174, 2010.)



—JNAM

Pollen's energy-efficient water conservation. The outer layer of a pollen-grain wall generally includes apertures through which the grain can gain or lose water. When in an arid environment, pollen grains avoid becoming dangerously dry by undergoing a process called harmomegathy—the grain's apertures are effectively sealed until the pollen lands in a wetter location. For more than a century, scientists have known that wall structure helps determine the form that a pollen grain assumes after harmomegathy. Now Harvard University's Jacques Dumais, former Harvard student Eleni Katifori, and colleagues have presented the first quantitative model of the process and confirmed it with electron micrographs such as shown here (the scale bars represent 20 μm). The model incorporates the classic result that stretching a surface costs a lot of energy; instead of stretching, the grain surface bends as the wall folds onto itself to avoid further desiccation. The

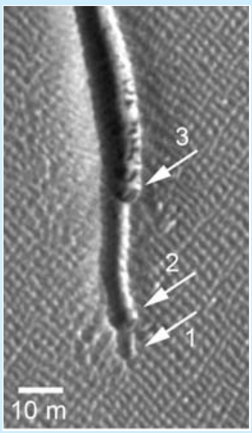


References

1. M. Haider, S. Uhlemann, E. Schwan, H. Rose, B. Kabius, K. Urban, *Nature* **392**, 768 (1998).
2. P. E. Batson, N. Dellby, O. L. Krivanek, *Nature* **418**, 617 (2002).
3. O. L. Krivanek, M. F. Chisholm, V. Nicolosi, T. J. Pennycook, G. J. Corbin, N. Dellby, M. F. Murfitt, C. S. Own, Z. S. Szilagyi, M. P. Oxley, S. T. Pantelides, S. J. Pennycook, *Nature* **464**, 571 (2010).
4. J. C. Meyer, A. Chuvilin, G. Algara-Siller, J. Biskupek, U. Kaiser, *Nano Lett.* **9**, 2683 (2009).
5. C. Jin, F. Lin, K. Suenaga, S. Iijima, *Phys. Rev. Lett.* **102**, 195505 (2009).
6. N. Alem, R. Erni, C. Kisielowski, M. D. Rossell, W. Gannett, A. Zettl, *Phys. Rev. B* **80**, 155425 (2009).
7. K. Suenaga, Y. Sato, Z. Liu, H. Kataura, T. Okazaki, K. Kimoto, H. Sawada, T. Sasaki, K. Omoto, T. Tomita, T. Kaneyama, Y. Kondo, *Nat. Chem.* **1**, 415 (2009).
8. O. L. Krivanek, N. Dellby, M. F. Murfitt, M. F. Chisholm, T. J. Pennycook, K. Suenaga, V. Nicolosi, *Ultramicroscopy* (in press).
9. M. Kuwabara, W. Lo, J. C. H. Spence, *J. Vac. Sci. Technol. A* **7**, 2745 (1989).

lily grain in panel a, for example, has an elongated aperture that allows harmomegathy to proceed somewhat like the way in which one makes a cone by connecting the edges of a disk that has had a slice removed. Strictly followed, that process yields vertices with high concentrations of bending energy; in reality the lily grain stretches a little at the vertices and ends up looking like a US football. The other grains illustrated in the figure have built on the same simple physics—avoid stretching and kinks—to achieve more intricate but equally effective harmomegathic responses. (E. Katifori et al., *Proc. Natl. Acad. Sci. USA* **107**, 7635, 2010.) —SKB

Water-carved gullies on Mars. Carved into many Martian dunes are narrow, sinuous channels. Studies of their morphology and laboratory simulations suggest that the likely origin of the gullies is surface or near-surface water ice that melts and forms a flowing slurry of sandy debris. Dennis Reiss and colleagues at the University of Münster's Institute for Planetology report new evidence for such transient liquid water. Their observations rely on data from the High Resolution Imaging Science Experiment, a camera on the *Mars Reconnaissance Orbiter* that provides nearly 10 times the resolution of the camera aboard the earlier *Mars Global Surveyor*. Armed with 23 sequential HiRISE images of the Russell crater dune field in Mars's southern hemisphere over two successive Martian years (spanning November 2006–May 2009), the researchers uncovered signs of multiple flow events that, as seen in this image, deepen and widen the channels. They also observed gullies lengthening over the course of the early Martian spring. Factoring in near-IR reflectance data, which tracked the melting of frozen carbon dioxide, and calculations of daily springtime temperature profiles at the surface, they discount dry flows and CO_2 flow mechanisms; they instead conclude that the gully changes are best explained by the seasonal melting of small amounts of water ice. (D. Reiss et al., *Geophys. Res. Lett.* **37**, L06203, 2010.) —RJF



Cement is denser than it's cracked up to be. When chemically modified with water in a process called hydration, cement morphs into the durable binder that holds gravel, sand, and other additives together to form concrete—the most used manmade material in the world. The main constituent of hydrated cement is $CaO\text{-}SiO_2\text{-}H_2O$ (called C-S-H) in the form of nanoscale colloidal aggregates, the size, shape, and packing of which are crucial to the ultimate strength and stability of concrete. The solid C-S-H nanoparticles are generally thought to be analogous to the claylike minerals tobermorite and jennite, mixed with calcium hydroxide. But new neutron-scattering studies by Jeffrey Thomas and Hamlin Jennings of Northwestern University and Andrew Allen of NIST in Gaithersburg, Maryland, show that C-S-H has a higher-than-expected atomic packing density. The mass density of solid C-S-H is roughly 10% higher than that of a mixture of its widely used mineral analogues with the same composition. The result has important implications for the modeling of cement paste. (See, for example, PHYSICS TODAY, November 2009, page 23, where that model's starting point is dry tobermorite.) The researchers also investigated the composition and density of C-S-H cured at elevated temperatures and with various additives. In particular, they found that curing the cement at 80 °C led to a lower atomic packing density. Such atomic packing variations suggest the possibility to control chemical shrinkage and the associated cracking of concrete. (J. J. Thomas, H. M. Jennings, A. J. Allen, *J. Phys. Chem. C* **114**, 7594, 2010.) —SGB

Maglevs for ships. Several approaches have been devised for suppressing the rolling motion of ships at sea. Active systems that position a movable mass to provide a countering torque can rapidly damp the rolling, but the inherent friction not only is noisy but also produces constant wear. Researchers from the Korea Institute of Machinery and Materials recently demonstrated that the technology employed to reduce friction in magnetically levitated trains can do the same for ships. Indeed, their antirolling device is essentially a maglev train car on a short track that runs side to side across the ship's midline. For the demonstration, the team built a 118-kg, small-scale model with the cross-sectional shape of a twin-hulled catamaran. A C-shaped, 4-kg mass—the "train car"—wrapped around a 1-m-long rail along the top of the model; electromagnets at the bottom of the mass faced the rail from underneath and provided the levitating force. Mounted in the rail was a linear motor, like those used to propel maglev trains (and some roller coasters). Whereas the more common rotary motors produce torque, linear motors produce linear forces. In the researchers' setup, as the motor controller received signals from a tilt sensor on the ship, it quickly moved the mass to the appropriate position to damp the rolling motion. In tests, the model ship's free oscillations were suppressed within 4 seconds. Though it is more expensive than conventional alternatives, the researchers think maglev antirolling technology could have broad potential, from pleasure boats to oceanographic research vessels. (C. H. Park et al., *Rev. Sci. Instrum.* **81**, 056102, 2010.) —RJF ■