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November 2013
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Arecibo at 50

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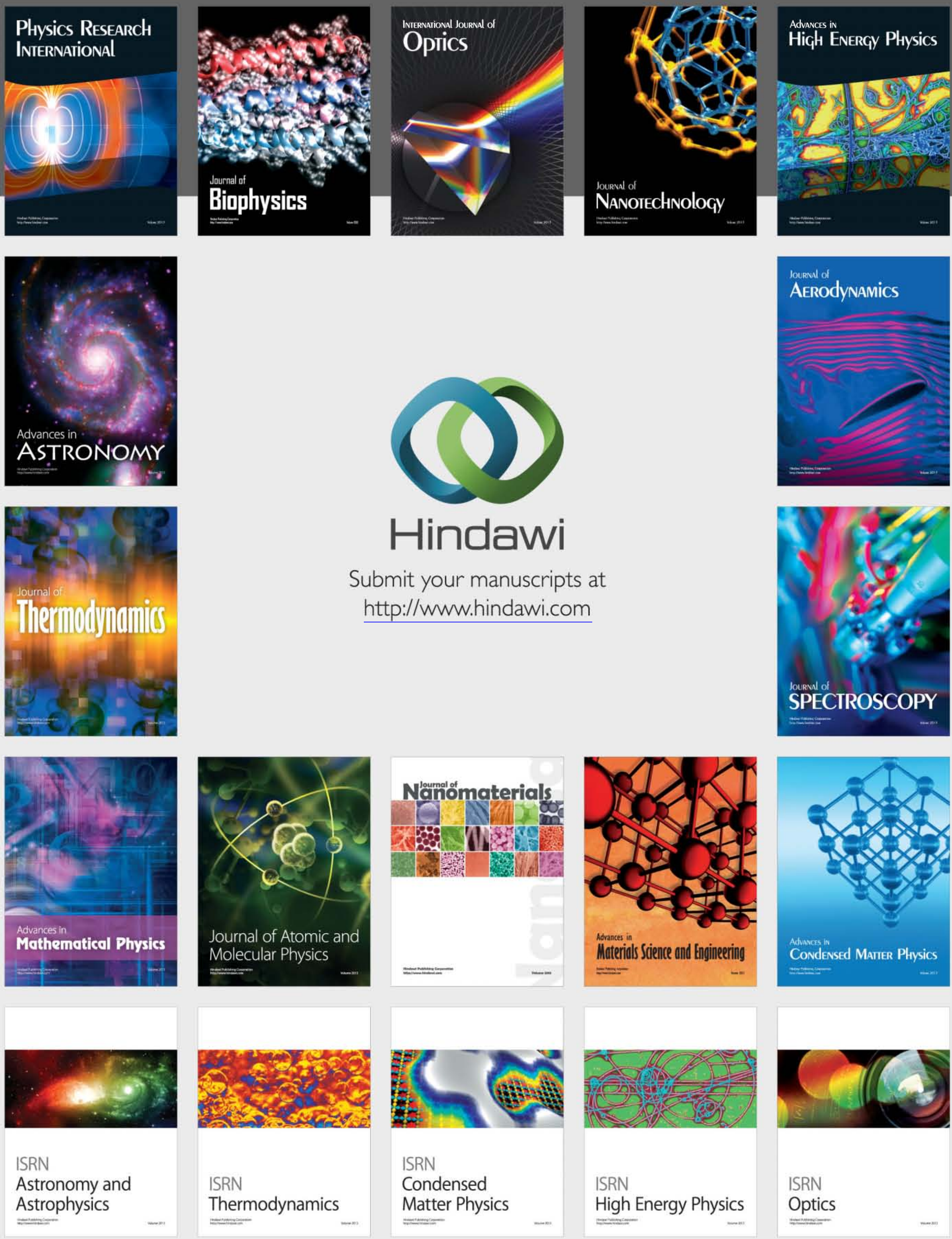
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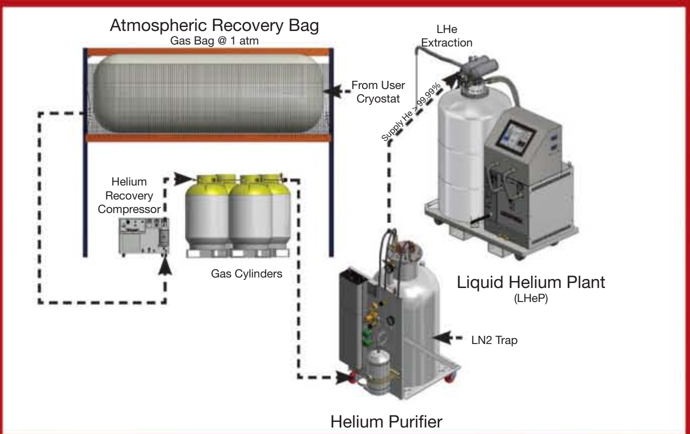

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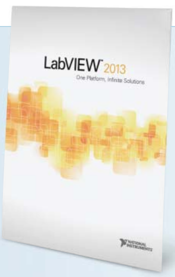

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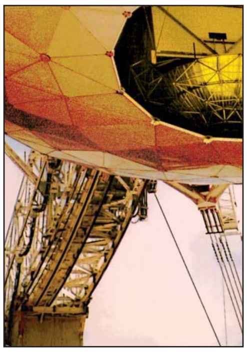
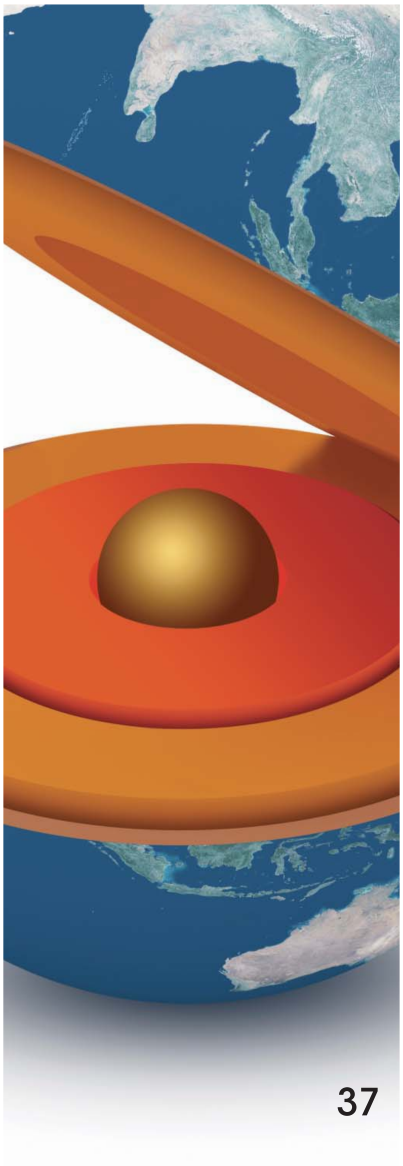
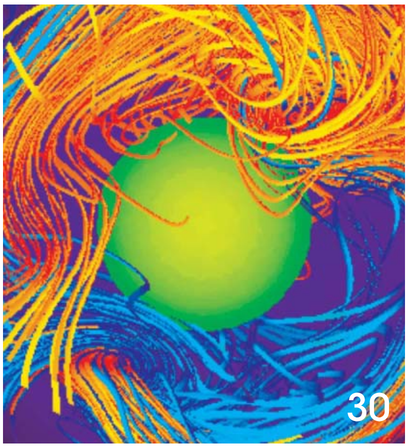


cover: Suspended high above the Arecibo Observatory's 300-meter-diameter dish is this structure, the so-called Gregorian dome. Inside are mirrors that correct for the dish's spherical aberration by focusing its reflected radio waves to a single point. On 1 November of this year, the observatory celebrates its golden anniversary. To honor its first 50 years, Daniel Altschuler and Chris Salter, in their article beginning on page 43, offer a brief history of Arecibo, with an emphasis on its contributions to astrophysics.





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physicstoday Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page physicstoday

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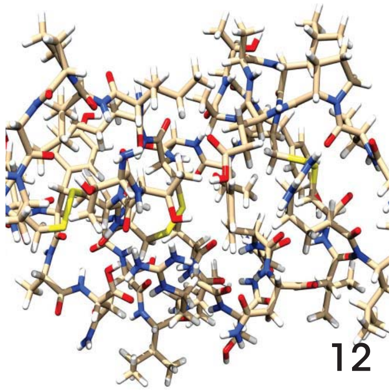

Commentary

Open-source hardware for research and education

Physicists are established leaders in making their work accessible to the whole community. An example is the electronic repository of open-access e-prints at arXiv.org, now more than 20 years old. As some disciplines struggle to develop centralized archives for their fields, the arXiv has grown to house more than 825 000 articles in physics and other fields; some subfields, in fact, have nearly all their articles there. Access to such a large body of literature provides obvious benefits to the physics community. The greatest is that not only does it provide us with the ability to "stand on the shoulders of giants," but it ensures that we are standing on the tallest shoulders, regardless of how limited our local institution's library might be.

The software industry has had a similar revolution of shoulder-standing, in the form of the free and open-source computer software movement. Free and open-source software (FOSS) is available in source-code form and can be used, copied, modified, and redistributed without restriction, or with restrictions only to ensure that it remains open to future recipients and users. Open-source development is decentralized, transparent, and participatory, in contrast to the standard black-box, top-down, and secretive commercial approach. First widely demonstrated with the incredibly successful Linux, FOSS has become integral to society: Much of the internet now relies on it. FOSS is becoming the dominant approach for software development simply because it is superior.[1] With open-source development, more people are collaborating to solve problems, and users as a group are smarter than any one individual.

Physicists are well acquainted with FOSS: Some of the best simulation and research tools are based on it. In addition, many physicists have begun to use FOSS in the classroom. For example, the Open Source Physics project enhances computational-physics education by providing computer-modeling tools, simulations, and curricular resources.[2] Physicists are also already acquainted with the open-source culture of sharing good ideas. Academic physicists, who dedicate their lives to information sharing as researchers and teachers, even have a well-established gift culture solidified in the tenure process. You get tenure based on how much you have given away—the more valuable the better—not on how much you hoard.

That scientific sharing tended until recently to be focused on what could be published in academic articles—ideas or software, as it were. No more. Now the open and collaborative principles of FOSS are being transferred to designs for scientific hardware, with innovative digital manufacturing providing an unprecedented opportunity to radically reduce the costs of equipment for experimental research and education.[3,4]

Two recent open-source design and production developments are driving those reductions: Arduino microcontrollers and the RepRap three-dimensional printer. The new microcontrollers (http://www.arduino.cc) are a family of low-cost circuit boards, each with a core processor, memory, and analog and digital input/output peripherals through which they can sense and affect their immediate surroundings. The microcontrollers are relatively easy to operate and have been used in many research and education settings,[5] including student lab kits and basic equipment like photogates, which can precisely time the interruption of a light beam at a fraction of the commercial cost. One of the most powerful present uses for Arduinos is in the open-source 3D printer known as a RepRap (http://reprap.org), a self-replicating rapid prototyper capable of synthesizing approximately 50% of its own components. A RepRap can be built for less than $600, which makes rapid prototyping accessible to most physics laboratories.[4]

The 3D printing process is a sequential layering operation in which an extruder heats and expels a filament of the working material—such as acrylonitrile butadiene styrene, the plastic used for Legos—through a nozzle to deposit a 2D layer; the extruder then advances a step in the vertical direction and the process repeats (see PHYSICS TODAY, October 2011, page 25). The RepRap uses computer-assisted drafting (CAD) designs, which can be shared easily over the internet. A useful CAD program for the mathematically adept is OpenSCAD (http://www.openscad.org), an open-source application that takes as its input a script describing the geometric specifications of an object. Once a user creates a design, anyone can quickly customize it. Dozens of designs for scientific equipment are already flourishing in Thingiverse, a free and open repository for digital designs (http://www.thingiverse.com). Thingiverse also maintains an application that allows OpenSCAD scripts to be easily manipulated.

To appreciate the elegance of the open-source hardware design approach, consider the recently developed open-source optics library of customizable printed designs[4] that can be rendered with off-the-shelf parts and Arduino microprocessors (http://www.thingiverse.com/jpearce/collections/open-source-optics). The collection of inexpensive 3D-printable components, from simple fiber-optic cable holders to automated filter-wheel changers, dramatically reduces the cost of optics equipment in labs and classrooms. For example, to outfit an undergraduate teaching lab with 30 optics setups that include 1-meter optical tracks, lenses, adjustable lens holders, ray-optics kits, and viewing screens would cost less than $500 with open-source hardware, compared with approximately $15 000 for commercial versions.[4]

Tools for physics experiments are less expensive to design and print than

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to buy, particularly if another user has already started the design work. Saving money in the lab, though, is only one benefit. More importantly, the user can customize optics equipment or other physics apparatus and automate its manufacture, which ensures that the components are exactly what the specific research needs. It also saves time: Printing a predesigned component is much faster than going to a lab supply store or ordering the component online. For researchers, the value of timely access to experimental equipment can hardly be overstated.

Perhaps the most important point about free and open-source hardware is that a user who alters an open-source design is required to share any improvements with the rest of the community. By taking that extra step, users help accelerate the availability of open-source scientific hardware for everyone, and they will directly benefit as the international open-source community takes the design, further improves it, and re-shares the results. You probably know of people who already design some of their own equipment. If they share it, the user community will do equipment R&D for free, and all will be better for it.

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Letters

More on black holes and quantum information

The article "Black holes, quantum information, and the foundations of physics," by Steve Giddings (Physics Today, April 2013, page 30), reviews the challenges that black holes present to the foundational principles of unitarity and causality in quantum theory. The problems and paradoxes of black holes were inherent in the earliest discussions of the Hawking effect, and were brought to the attention of many physicists by Stephen Hawking himself. In reviewing the imaginative attempts, some of them quite radical, to reconcile black holes with quantum mechanics, Giddings ignores the simplest possibility of all: that because of quantum effects, a classical event horizon never forms.

The widespread belief that gravitational collapse leads inevitably to an event horizon is based on an essentially classical view of the collapsing matter and its equation of state, a view that rests, in turn, upon the assumption that quantum effects are negligible on macroscopic scales. This prejudice persists despite voluminous experimental evidence to the contrary confirming the nonlocal—but certainly not acausal—appearance of quantum phase coherence in macroscopic systems as varied as superfluids, superconductors, low-temperature atomic gases, Einstein-Podolsky-Rosen entangled photon pairs, squeezed light, and Aharonov–Bohm interference experiments. To those may be added the standard model itself, which features both quark and gluon condensates in quantum chromodynamics, and a Higgs vacuum condensate, which is uniform and coherent in space at very large distances.

The usual classical statement that local curvatures are small at the horizons of large black holes is irrelevant to the macroscopic and nonlocal phase correlations of the quantum vacuum. As a result of those nonlocal correlations, coherent vacuum stresses can grow very large in the vicinity of the apparent horizon, the smallness of the local curvature there notwithstanding. Far from violating fundamental principles, large vacuum stresses on the horizon are the result of standard one-loop calculations of quantum fluctuations in black hole spacetimes[1] and are a generic feature of states that approach the ordinary Minkowski vacuum far from the black hole.[2,3] Position-dependent vacuum stresses in black hole spacetimes do not violate the equivalence principle, any more than they do in the Casimir effect. Nor do such large stresses on the horizon rely on faster-than-light violations of microcausality, in contrast to the massive-remnant scenarios postulated by Giddings and illustrated in figure 4 of his article.

If quantum fluctuations and associated stress energies do become large at the locally defined apparent horizon of a forming black hole, then general arguments lead one to expect that a critical surface or phase transition should occur in the vicinity.[4] At such a phase boundary layer, the energy density ρ of the squeezed vacuum can increase very rapidly. Having positive vacuum energy ρ and negative pressure $p = -\rho$, the interior of the "black hole" acts as a repulsive core, preventing further collapse. The resulting stable, nonsingular endpoint of complete gravitational collapse, consistent with all quantum principles, is a gravitational vacuum condensate star, or gravastar.[5] It carries that name because its interior support relies on the energy of a vacuum condensate, with the same equation of state—though with a much larger magnitude—as the cosmological dark energy believed to be pervading our universe. Since $\rho + 3p < 0$, the only energy condition an interior vacuum condensate violates is the strong energy condition which prevents a black hole singularity from forming.

Once large quantum back-reaction effects at the horizon scale are admitted and a phase boundary layer takes the place of the event horizon, the very basis of the Hawking thermal evaporation and black hole entropy disappears. All the difficulties with black holes that arise when $\hbar \neq 0$ are eliminated and there is no enormous information loss to be accounted for. Observer dependence and all contradictions with information theory or quantum cloning are removed as well.

To be sure, new physics must take place within the thin quantum boundary layer replacing the classical horizon. The physical thickness of the transition layer is of order $\sqrt{R_S L_P} \approx (2 \times 10^{-16}\ \text{m})\sqrt{M/M_\odot}$, where $R_S = 2GM/c^2$ is the Schwarzschild radius, $L_P = \sqrt{\hbar G/c^3}$ is the Planck length, and $M_\odot$ is the solar mass.[5] Classical general relativity receives significant corrections only in that layer. Due to the layer's extreme thinness, distinguishing gravastars from classical black holes is astrophysically challenging, but by no means impossible, and may even be realized within this decade. Developing distinguishing predictions for astronomical observations is now an active field of research.

The important point is that an alternative exists that does not require abandoning well-established quantum principles of unitarity or microcausality. Moreover, in contrast to the rather more extreme or fanciful speculations discussed by Giddings and others over the years, this hypothesis has now surrendered itself to the normal scientific process of validation or falsification by observation and experiment.

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■ **On reading** Steve Giddings's article, I felt the need to share some information about the original work of Karl Schwarzschild.[1]

His solution contained no coordinate singularity; it had only the singularity at the origin. That was neither a mistake nor an oversight on Schwarzschild's part. By choosing a nontrivial scaling factor for the angular part of the metric, he had carefully avoided producing the coordinate singularity. As a side effect, such a choice results in a nonzero surface area for a sphere of zero radius. However, that result should not be a problem since one is not dealing with flat space anyway.

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■ **Giddings replies:** Emil Mottola and Ruslan Vaulin emphasize that there are different versions of massive remnant scenarios—with horizonless star-like objects replacing black holes. Fuzzballs, firewalls, and gravastars are examples. A black hole may form and then transition into a massive remnant, or a collapsing object may transition into a massive remnant just before it reaches the horizon. (Fuzzball supporters have varied between these possibilities.) In my article, space limited discussion to the first version, but many believe the latter version faces comparable challenges with locality and with observation.

Consider gravitational collapse of a fluid ball of mass M. Its density at horizon formation is around $10^{16}\,(M_\odot/M)^2$ g/cm^3, where $M_\odot$ is the mass of the Sun. With M the mass of our galactic black hole, Sgr A*, that density is about 1000 g/cm^3; for the largest known black holes, it is about 10^{-4} g/cm^3. Both densities are within well-explored regimes—the latter is less than the density of air.

In the conventional picture, a fluid element crossing the horizon is nearly freely falling. To avoid black hole formation, the element must suddenly accelerate enormously, enter a new state, and maintain sufficient acceleration to avert horizon crossing. If a static remnant were so produced, the external state and stress tensor could well be approximated by those of D. G. Boulware (Mottola and Vaulin's reference 1). The big question is what could provide a plausible dynamical mechanism for that drastic transition.

Apparently, the mechanism would have to be nonlocal, to stop the fluid just before the horizon, since the horizon is not a local construct. If a collision or explosion blew off the material on one side of the fluid during collapse, the ultimate horizon would be smaller, and a fluid element on the opposite side would have to nonlocally know not to suddenly accelerate. Such scenarios seemingly involve even more extreme and fanciful departures from conventional physics—including locality—than a small effect that allows information to "leak" from a black hole. Moreover, the latter nonlocality does not necessarily imply asymptotic acausality;[1] symmetries of the black hole are different from those of Minkowski space.

If a scenario in which a physical surface replaces the horizon were realized, one would expect radiation from accreting matter impacting the surface. Indeed, Avery Broderick, Abraham Loeb, and Ramesh Narayan constrain such radiation[2] to less than 1% of infalling energy for Sgr A* and conclude that it is all but certain that a surface replacing the horizon does not exist. Clearly, though, experimental constraints are improving.

Tarun Biswas points out that Karl Schwarzschild used different coordinates. Schwarzschild's r should not be thought of as the usual radius; in his coordinates a geodesic continues through $r = 0$ to negative r. In general relativity, physics is independent of choice of coordinates, but the more easily interpreted choice for a radial coordinate is the conventional one determining areas of spheres.

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Notes on nuclear physics in 1932

The article by Joseph Reader and Charles Clark, "1932, a watershed year in nuclear physics" (PHYSICS TODAY, March 2013, page 44), was most interesting and warrants a few comments.

On page 46, the authors put "the Cavendish Laboratory in Oxford." The Cavendish, first known as the Devonshire Laboratory, is at Cambridge University. It was established in 1874 by William Cavendish, the seventh duke of Devonshire, who donated the funds for it and served as university chancellor. His relative, Henry Cavendish, was a chemist and physicist who first "weighed the earth." The lab's first professor was James Clerk Maxwell, who renamed the facility to commemorate the contributions of both Cavendishes.

Reader and Clark also mention Ernest Rutherford's frugality, which is best understood in the context of his modest background as the son of a farmer. A second reason for his fiscal restraint is that research funding was not plentiful in the time between the two world wars, and the Depression did not help. Rutherford's frugality is corroborated by a quote related to me by one of my professors at Birmingham University in the UK, Philip Moon, a student of Rutherford's in 1928–31, who quoted him as saying, "We have no money, so we have to think." More important, Rutherford was known for doing and encouraging innovative work with simple experiments. Also, as Moon related it, Rutherford encouraged independent thought, even at the expense of precious resources. Moon told us about how someone had complained to Rutherford that a certain investigator spent laboratory resources on useless research. Rutherford responded, "Let him find out for himself, and he will not do it again."

The authors' mention of John Cockcroft and Ernest Walton brings back memories of one member in their group, another of Rutherford's students: William Burcham, who was head of the physics department when I entered Birmingham University. He had been intimately involved in the upgrade of the Cockcroft–Walton apparatus to 2 MV. The upgrade was made possible through a gift of £4000 from Herbert Austin, the automobile manufacturer.[1]

I also offer a brief comment on positron emission tomography (PET) imaging. Although carbon-11 is indeed used for some medical imaging applications—prostate cancer detection, for example—its relatively short half-life of around 20 minutes requires a cyclotron on hospital grounds to produce it. The $2 million expense of setting up a medical cyclotron for isotope production impedes the widespread use of ^{11}C. The more preferred and widely used isotope for PET imaging is fluorine-18; its half-life of around 110 minutes makes it more practical to use. Furthermore, ^{18}F-labeled fluorodeoxyglucose, a glucose analogue, provides a wide range of medical applications.

Some of us can still relate to Rutherford's era through the privilege of having been taught by his students.

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search and discovery

Helioseismology plumbs new depths

The technique has yielded the most detailed picture to date of the subsurface flows that circulate plasma between the Sun's equator and poles.

For more than two decades, solar astronomers have known that the magnetized plasma at the Sun's surface gradually drifts from the equator to the poles. It follows, then, that somewhere in the solar interior that plasma must return to the equator—after all, the Sun's poles do not become more massive with time. But whereas surface velocities can be detected by line-of-sight Doppler shifts, advection of passive tracers, and other straightforward means, interior flows are hidden by the Sun's opaque photosphere. As a result, the meridional return flow has long eluded definitive detection.

Hints of an equatorward flow can be seen in the motion of so-called supergranules, convection cells that cycle plasma between the Sun's interior and its surface. The smallest supergranules drift poleward, presumably carried by surface currents. But some larger granules can be seen to move upstream, toward the equator. One theory is that the larger cells penetrate deeper into the solar interior and therefore may be getting caught in the equatorward undertow. Based on that theory and a few simplifying assumptions, David Hathaway of NASA's Marshall Space Flight Center in Huntsville, Alabama, estimated last year[1] that the meridional flow turns equatorward at a depth of about 50 Mm, about 1/14 the solar radius $R_\odot$.

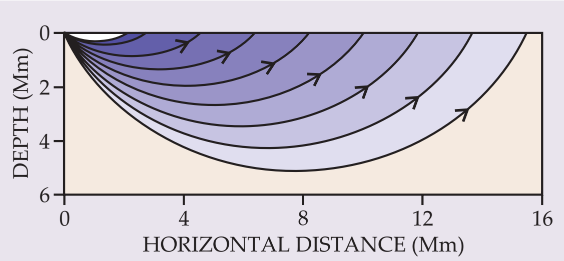

Figure 1. Acoustic rays that propagate into the Sun's interior get refracted and bent back toward the surface in smooth arcs. Each ray emerges at a distance that's roughly proportional to the depth of its trajectory (5 Mm is equal to about 1/140 the solar radius). Because acoustic waves travel faster with subsurface currents than against them, flow velocities along a ray's trajectory can be inferred from the directional dependence of its travel time.

Junwei Zhao of Stanford University in Palo Alto, California, and coworkers there and at NASA's Goddard Space Flight Center in Greenbelt, Maryland, have now detected the equatorward return using a more direct and precise technique: time–distance helioseismology.[2] Analogous to terrestrial seismology, helioseismology uses correlations between surface acoustic waves to infer properties of the solar interior. (See the article by John Harvey, PHYSICS TODAY, October 1995, page 32.) The technique has been around for decades, but recent refinements and improved observational data have allowed Zhao and coworkers to probe meridional velocities to depths of 170 Mm, nearly ¼ the way to the Sun's center. And in a result that's bound to baffle some solar-dynamo theorists, the researchers find not one flow reversal but two.

Solar echoes

Virtually all solar plasma flow occurs in an outer shell known as the convective zone, which spans radial distances between 0.7 $R_\odot$ and the solar surface. The complex, three-dimensional flows in the convective zone help transport heat generated in the solar core to the cool surface and give rise to the dynamo that's responsible for the Sun's magnetic dipole and 11-year activity cycle. (For more on magnetic dynamos, see the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40, and the article by Peter Olson on page 30 in this issue.) Beneath the convective zone, the Sun is essentially a uniformly spinning ball of gas.

Meridional flows in the convective zone are difficult to detect in part because they're relatively small. Whereas mean rotation speeds and velocity fluctuations are typically around 1 km/s, the net meridional flow peaks at around 10–20 m/s.

In the 1990s Thomas Duvall Jr, a solar astronomer at NASA Goddard, and coworkers introduced time-distance helioseismology as one way to detect the subtle flows.[3]

Like all helioseismology techniques, time–distance helioseismology takes advantage of the fact that local density and temperature—and, therefore, the speed of sound—increase with depth in the solar interior. As a result, acoustic waves that propagate into the solar interior refract and bend back toward the surface. Treated as rays, they trace arcs like those depicted in figure 1. On reaching the surface, the rays are then reflected back into the interior; the depth of the trajectory is roughly proportional to the distance Δ between surface reflections.

Duvall's strategy was to cross correlate acoustic signals at points along a meridian to determine time lags between surface reflections as a function of Δ. Acoustic rays travel faster with subsurface currents than against them, so meridional flow velocities along a ray trajectory can be inferred from slight differences between north–south and south–north lag times. The effect is subtle: For deep trajectories, the flow may shave or add less than one second per hour of travel time. Nonetheless, with enough data and an appropriate model of the solar interior, one can rather precisely infer subsurface velocity profiles.

Starting in the 1990s, the Stanford group began applying Duvall's time–distance helioseismology approach to acoustical data collected by the Michelson Doppler Imager, which was launched aboard the *Solar and Heliospheric Observatory* in 1995. Those studies clearly showed the poleward velocity growing smaller with depth, but they failed to find a reversal.

Center-to-limb effect

Last year, Zhao and his coworkers began analyzing data from the recently launched *Solar Dynamics Observatory*'s Helioseismic and Magnetic Imager (HMI) with the hope that the instrument's higher-resolution images might allow deeper and more accurate measurements of the meridional profile. Soon, however, they encountered a troubling inconsistency.

Surface oscillations can be detected

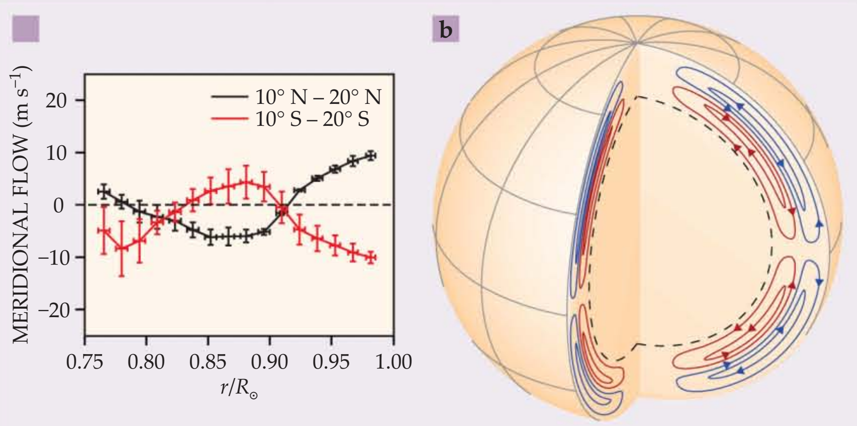

Figure 2. Profiling the depths. (a) Time–distance helioseismology measurements of subsurface velocity profiles in the Sun's northern (black) and southern (red) hemispheres suggest that the meridional flow of plasma is poleward at radial distances r greater than about 0.9 $R_\odot$, equatorward between roughly 0.8 $R_\odot$ and 0.9 $R_\odot$, and poleward below that ($R_\odot$ is the solar radius). By convention, northerly flow is positive. **(b)** The observed profiles suggest that two distinct circulation cells transport solar plasma from the equator to the poles and back. The black dashed line indicates the bottom of the convective zone. (Adapted from ref. 2.)

in solar images via a number of observables; they show up as changes in surface brightness or as oscillations in the Doppler shifts of various spectral lines, for instance. In principle, all those observables should carry identical acoustic information. But the Stanford researchers were finding different results for each observable. "For months, we thought that our approach might have been fundamentally flawed," recalls Zhao. "It was very discouraging."

As a check, the team calculated eastward velocities along the Sun's equator using HMI images collected over a 10-day span in December 2010.[4] Those velocities should be independent of longitude, but the group's analysis indicated larger-than-average velocities in the right, or eastern, half of the solar disk and smaller-than-average velocities in the left. Something was creating the illusion of an extra velocity component—in some cases as large as 10 m/s—directed from the center of the solar disk to its limb.

Zhao and his colleagues concluded that the discrepancy had to have been a systematic error. Assuming it affects meridional measurements in the same way it does equatorial ones, it would artificially bias flow velocities toward the poles and potentially mask any equatorward flow. Indeed, when the researchers subtracted the center-to-limb components from meridional profiles calculated with different observables, the resulting profiles were all consistent with one another. "We still don't understand what's causing the effect," says Zhao. "But the correction method appears to be robust."

The Sun's conveyor belts

In the new work, the researchers applied the center-to-limb correction to a helioseismology analysis of two years of HMI data. Figure 2a shows resulting flow profiles averaged over 10°-wide latitudinal bands in the Sun's northern and southern hemispheres. Two distinct reversals can be seen, at radial distances of about 0.9 $R_\odot$ and 0.8 $R_\odot$. Such profiles imply a large-scale flow field consisting of two distinct circulation cells, as illustrated in figure 2b.

A two-cell meridional circulation doesn't come as a complete surprise. Other researchers have speculated on its existence from indirect experimental evidence and numerical simulations. "But this new evidence is currently the most compelling," says Mark Miesch of the National Center for Atmospheric Research in Boulder, Colorado.

The results could prove problematic for some solar dynamo theories. In particular, one popular class of models—the so-called flux-transport dynamo models—has long relied on a single circulation cell to explain phenomena associated with the 11-year solar activity cycle.[5] For instance, sunspots—cool, dark patches on the solar surface that form when magnetized plasma bubbles up from the convective zone's floor—appear at mid latitudes early in the cycle and at progressively lower latitudes as the cycle proceeds.

Flux-transport dynamo models attribute that equatorward migration to the meridional flow at the bottom of the convective zone. But in a two-cell pattern—or any even-celled pattern—that flow is toward the poles, not the equator.

A potential saving grace for the flux-transport models is the possibility of a third meridional cell squeezed in between 0.7 $R_\odot$, the radial distance of the convective-zone floor, and 0.75 $R_\odot$, the distance corresponding to Zhao and coworkers' deepest measurements. The HMI will continue collecting data for at least three more years, which should allow Zhao and his coworkers to extend their measurements deeper, perhaps to the convective zone's floor. If those studies don't reveal a third reversal, there may be little wiggle room left for flux-transport dynamo models of the solar cycle.

Ashley G. Smart

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Ceramic nanolattices hold up under pressure

At the right size scale, a brittle substance becomes strong and springy.

Apply a large enough stress to a piece of brittle material and it will break—most likely at a preexisting flaw or weak spot. Flaws thereby reduce the fracture strength of real materials relative to their theoretical maxima, sometimes by orders of magnitude. That reduction can be well predicted by the expected statistical distribution of flaw sizes, which depends on the sample's size.

Reduce the sample's dimensions below a micron or so and the picture changes. Submicron single crystals of metal or ceramic, whether they contain flaws or not, are much stronger than their bulk counterparts.[1] Furthermore, a submicron sample is no more likely to break at a flaw than anywhere else. The reasons for that size effect remain unclear. But it's been noted that fracture-resistant biomaterials—such as shells, bone, and tooth enamel—are made up of just such submicron mineral crystals embedded in a protein matrix.[2] (For more on the structure and properties of bone, see the article by Rob Ritchie, Markus Buehler, and Paul Hansma, PHYSICS TODAY, June 2009, page 41.) The secret of their strength may lie in the size effect.

Now Julia Greer and colleagues have taken a step toward exploiting the size effect to produce strong, lightweight materials.[3] They fabricated lattices with submicron dimensions, such as the one shown in figure 1, made up of hollow struts of titanium nitride, a brittle ceramic. Under deformation, the lattices exhibited material properties close to the theoretical limit for TiN.

Smaller is stronger

Two years ago researchers at HRL Laboratories in Malibu, California, and their collaborators (including Greer) developed a technique for building hollow metal lattices.[4] (See PHYSICS TODAY, January 2012, page 13.) Those lattices had some extraordinary material properties—most notably, their ultralow density. But their unit cells had dimensions of hundreds of microns to millimeters, far too large to exhibit the size effect.

Greer and colleagues used similar techniques to construct their TiN lattices, with some important modifications to allow them to reach a 100-times-smaller size scale. First, to produce a polymer scaffold using a negative photoresist (a liquid polymer that hardens when exposed to bright light), they programmed a computer-controlled focused laser to "draw" the desired three-dimensional structure in the liquid photoresist. Then they deposited alternating monolayers of titanium and nitrogen onto the scaffold to form a 75-nm layer of TiN. Finally, they etched away the polymer scaffold using an oxygen plasma treatment.

To test the strength of their TiN lattices, the researchers applied a compressive load while observing the sys-

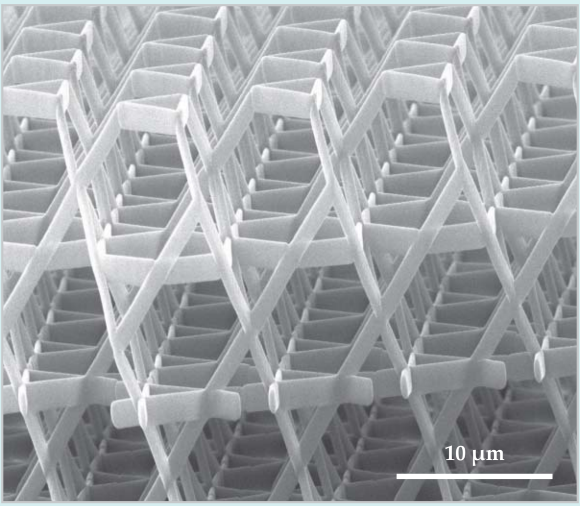

Figure 1. A hollow ceramic nanolattice with a three-dimensional kagome structure. Each of the several-micron-long struts is a tube with an elliptical cross section, 1 μm × 250 nm, and a wall thickness of 75 nm. (Courtesy of Lucas Meza and Lauren Montemayor.)

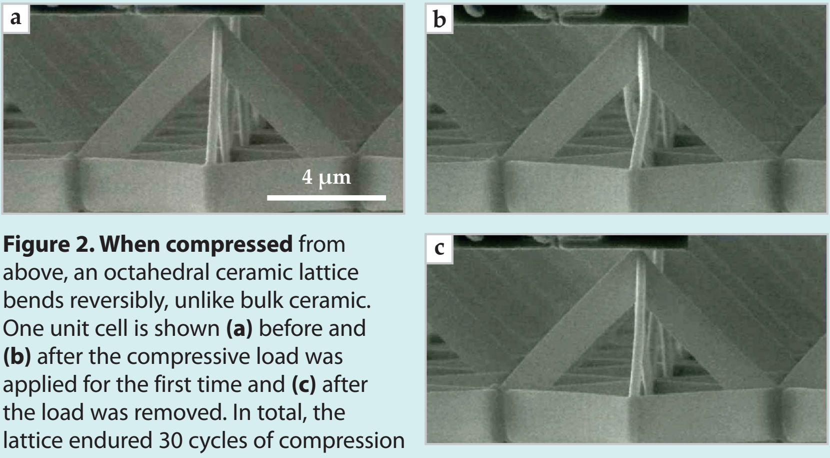

Figure 2. When compressed from above, an octahedral ceramic lattice bends reversibly, unlike bulk ceramic. One unit cell is shown **(a)** before and **(b)** after the compressive load was applied for the first time and **(c)** after the load was removed. In total, the lattice endured 30 cycles of compression and still recovered nearly its original shape. (Adapted from ref. 3.)

tem with a scanning electron microscope, as shown in figure 2. When an octahedral lattice was distorted until it broke, it exhibited a tensile strength of 1.75 GPa. (Even though the lattice as a whole was compressed, the failure occurred in a component that was under tension.) In comparison, the theoretical tensile strength for flawless TiN is estimated to be 3.27 GPa. Typical real bulk samples of TiN and other brittle ceramics have tensile strengths in the tens to hundreds of megapascals.

Furthermore, unlike bulk TiN, the lattices could bend significantly without breaking and spring back nearly to their original shape, even after 30 cycles of deformation. "Ceramics are not supposed to do that," says Greer. "Imagine a piece of chalk that was bending and deforming and never breaking!"

The Caltech researchers are continuing to experiment with different lattice structures and materials, but so far their lattices are just 100 μm or so on a side. Drawing the lattice into the photoresist with a single focused laser gives them a lot of flexibility in the structures and dimensions they can achieve, but it doesn't lend itself to mass production. As Greer explains, "That is the biggest roadblock" to developing engineering materials that capitalize on the size effect. "What someone needs to do now is develop a manufacturability route."

Johanna Miller

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A powerful quantum chemical method tackles a protein

Previously limited to systems with a mere dozen or so atoms, coupled-cluster theory can now manage hundreds.

The fundamentals of theoretical chemistry are straightforward. A molecule's electrons and atomic nuclei interact via a Coulomb potential. Nuclei can usually be treated as stationary classical particles, and electrons can often be assumed to be nonrelativistic. Solving the Schrödinger equation thus yields a molecule's electronic structure and energy, from which one can derive reaction energies, spectroscopic properties, and other aspects of chemical behavior.

But the many-electron Schrödinger equation is too difficult to solve exactly. Computational chemists must develop simplifications that sacrifice some accuracy for the sake of efficiency. One approach, suitable for especially large or dynamic systems, is to treat just part of the molecule quantum mechanically and to simulate the rest classically. For their pioneering work on those quantum–classical hybrid models, Martin Karplus, Michael Levitt, and Arieh Warshel were awarded the 2013 Nobel Prize in Chemistry, which will be covered in detail in the December issue of PHYSICS TODAY.

Even when the entire system must be treated quantum mechanically, some approximations can still be made. (See the article by Martin Head-Gordon and Emilio Artacho, PHYSICS TODAY, April 2008, page 58.) One favorite approximation, coupled-cluster theory, is regarded as the gold standard for computational chemistry: It can compute relative energies to within 0.04 eV—accurate enough for most purposes—using just a tiny fraction of the computing time required for an exact solution.[1] But for large molecules, standard coupled-cluster theory is still far too computationally intense; one must typically resort to less accurate methods.

Frank Neese and colleagues at the Max Planck Institute for Chemical Energy Conversion have now developed an approach to coupled-cluster theory that reduces the difficulty of the calculation by a factor of 10^6 or more, while sacrificing little accuracy.[2,3] With it, they can compute coupled-cluster energies of molecules with several hundred atoms in a matter of days or weeks. Standard coupled-cluster calculations on the same molecules would take many thousands or even millions of years.

Hartree-Fock

The simplest useful computational chemistry method, and the one on which many others are based, is the Hartree–Fock method. In Hartree–Fock's predecessor, the Hartree method, the N-electron wavefunction Ψ is approximated as the direct product of N single-electron wavefunctions, or orbitals, φ_i: $\Psi(\mathbf{x}_1, \mathbf{x}_2, \ldots \mathbf{x}_N) = \varphi_1(\mathbf{x}_1)\varphi_2(\mathbf{x}_2) \ldots \varphi_N(\mathbf{x}_N)$, where $\mathbf{x}_i$ is the spatial position of the ith electron. The molecular orbitals φ_i are solved self-consistently: Each electron feels the electric field of all the other electrons, averaged over their respective wavefunctions. In modern implementations of the Hartree and other methods, the φ_i are written as linear combinations of a finite, predetermined set of basis functions, usually based on atomic orbitals. One aims to choose a basis that is large enough to be reasonably complete.

The Hartree method accounts for electron–electron repulsion in a rudimentary way. But in the true N-electron wavefunction, the electron positions are correlated in a way that can never be reproduced by the product of N single-electron wavefunctions. For one thing, electrons are identical fermions, no two of which can be in the same place at the same time. The Hartree–Fock method improves on the Hartree method by antisymmetrizing the wavefunction to account for the electrons' Fermi statistics. For a two-electron system, the Hartree–Fock wavefunction is proportional to

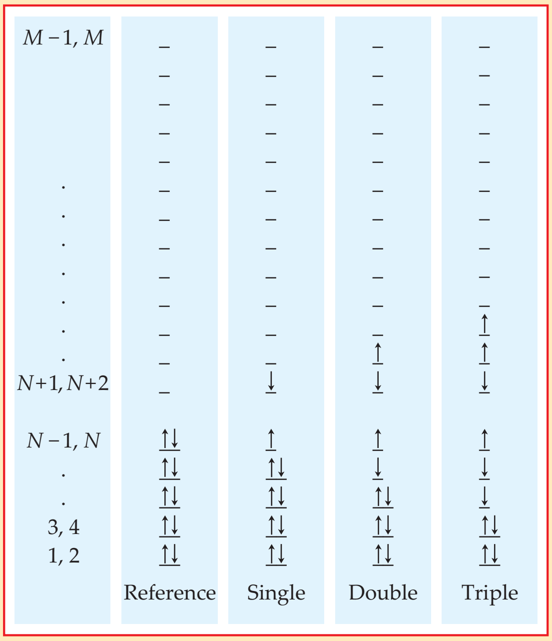

Figure 1. The *N* electrons in a molecule can be assigned to *M* molecular orbitals (*M*/2 spatial orbitals times two spin states) in many ways. In the so-called reference configuration, they're simply assigned to the *N* lowest-energy orbitals. But the true *N*-electron wavefunction is a linear combination of the reference configuration and configurations with one, two, three, or more electrons promoted into higher-energy orbitals. The single, double, and triple excitations shown here are merely examples of their kinds—there are many more, with any of the *N* electrons promoted to any of the *M* − *N* unoccupied orbitals. (Adapted from ref. 1.)

$\varphi_1(\mathbf{x}_1)\varphi_2(\mathbf{x}_2) - \varphi_2(\mathbf{x}_1)\varphi_1(\mathbf{x}_2)$, and so on for larger systems; the overall form is known as a Slater determinant.

But that's not good enough. Hartree–Fock still neglects the correlations that arise from Coulomb repulsion, and thus its predictions are often qualitatively incorrect. Recovering that remaining electron correlation—and more specifically, the correlation energy, defined as the difference between the exact energy and the best Hartree–Fock energy—is a major goal of computational methods such as those described below.

Coupled cluster

One way to improve on Hartree–Fock is to write the wavefunction as a linear combination of the Hartree–Fock, or "reference," Slater determinant and similar Slater determinants with one or more of the electrons promoted into higher-energy orbitals, as shown in figure 1. Within that space of linear combinations, one then optimizes the coefficient of each Slater determinant to find the lowest-energy eigenstate of the molecular Hamiltonian.

Because the excited orbitals, like the Hartree orbitals, are linear combinations of a finite number of basis functions, their total number M is finite. So in principle it's possible to consider all $M!/N!(M-N)!$ of the possible excited Slater determinants. That approach, called the full configuration interaction (CI) method, gives the exact solution within the constraints of the original basis set. But its computational intensity grows exponentially with N, so it's not practical for any but the very smallest systems.

Coupled-cluster theory approximates the full CI method by reducing the number of coefficients to be optimized. For example, in CCSD (for "coupled-cluster singles doubles"), only the one- and two-electron excitations have their own coefficients. The coupled-cluster wavefunction is no longer a simple linear combination of its constituent Slater determinants, so higher-order excitations aren't left out; instead, they're expressed in terms of one- and two-electron excitations. That approach treats two-electron correlations exactly and scales in intensity like N^6, but it's not quite accurate enough for chemical purposes. Adding a perturbative correction for triple excitations yields CCSD(T), which achieves chemical accuracy with N^7 scaling.

That's far better than the exponential scaling of the full CI. But CCSD(T) is still too slow to use on molecules with more than about a dozen atoms. And even as computers get faster and more powerful, it will take a 128-fold increase in speed to allow just a twofold increase in system size.

Linear scaling

There should be a way to do better. Electron correlation has long been recognized to be local: The correlations in one part of a molecule don't significantly depend on those in another. It ought, therefore, to be possible to break up a molecule into segments and calculate the correlation energy of each—with the overall calculation scaling linearly, like N. But how to implement such a calculation is far from obvious.

Rather than chopping up the molecule in real space, Neese and colleagues approach the problem by compressing information in orbital space. In 2009 they turned to the decades-old concept of pair natural orbitals (PNOs): For each electron pair, one transforms the space of excited molecular orbitals so as to capture that pair's contribution to the correlation energy in as few orbitals as possible.

By truncating the wavefunction expansion to include only those PNOs that are expected to significantly contribute, Neese and colleagues drastically reduced the complexity of a coupled-cluster calculation.[4] But calculating all of the PNOs took time. In the end, the PNO-based methods were a big improvement over standard coupled-cluster methods, but their scaling was nowhere near linear.

Over the past two years, Neese had his postdoc Christoph Riplinger (now at Princeton University) look for a faster method for calculating the PNOs. Inspired by Hans-Joachim Werner and colleagues' success[5] in representing excited orbitals as sums of local projected atomic orbitals[6] (PAOs), Riplinger developed a way to expand the PNOs in terms of PAOs. "Getting the integral transformations to scale linearly was an incredibly difficult bookkeeping problem," explains Neese. "Christoph was able to look far enough ahead into the calculation to figure out which integral is needed when and where—and why."

Furthermore, Neese developed an efficient way of prescreening electron pairs to exclude those whose excitations don't significantly contribute to the cor-

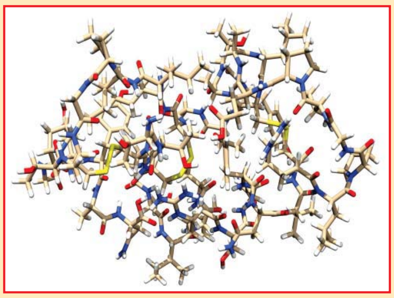

Figure 2. Crambin, with 644 atoms, is relatively small for a protein. But it's the largest molecule to be studied with coupled-cluster theory to date.[3]

relation at all, thereby reducing the complexity of the calculation by as much as 90%. Technically, any process that considers electrons two at a time must scale at least like N^2. But the prescreening was a small enough part of the whole calculation that the overall method scales almost like N.

Earlier this year Riplinger and Neese presented their nearly linear method for CCSD,[2] which they've dubbed "domain-based local PNO-CCSD." And now they and their colleagues have applied the same methods to the perturbative triples correction, resulting in DLPNO-CCSD(T).[3]

Large molecules

Even with all the approximations and truncations made by DLPNO-CCSD(T), the researchers found that it still captures more than 99.8% of the standard CCSD(T) correlation energy for a test set of medium-sized organic molecules. And they were able to calculate coupled-cluster energies for far larger molecules than had ever been possible before, including the linear hydrocarbon $C_{150}H_{302}$ and the 644-atom protein crambin, shown in figure 2. "I was remembering that a few years back, Filipp Furche and John Perdew presented a calculation on the crambin molecule using RI-DFT," says Neese, referring to resolution of the identity density-functional theory, the most efficient DFT method.[7] "That was a spectacular calculation in 2006." By working with the three-dimensional electron density rather than the 3N-dimensional N-electron wavefunction, DFT has a natural efficiency advantage over wavefunction methods, so it's often the approach of choice for studying large molecules. But its accuracy has yet to rival that of CCSD(T).

Neese and colleagues are continuing to work toward making their DLPNO-based coupled-cluster methods as useful as possible for users' calculations. For example, they hope to develop a code to treat molecules such as ozone, which aren't easily studied with coupled-cluster theory because they have unpaired electrons and aren't well approximated by a single reference state. They plan to make all their methods available to users via their software package ORCA.

Johanna Miller

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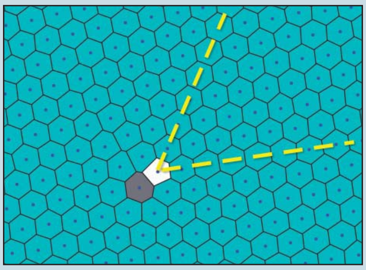
physics update

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

How annoying is wind-turbine noise? As the harnessing of wind power as a renewable energy source has grown, so too has the debate over possible sleep loss and other physiological effects from the noise generated by wind turbines.

Primarily arising in aerodynamic boundary layers along the rotating turbine blades, the sounds are amplitude modulated, with a characteristic "swish" at a frequency of about 1 Hz. Periodic sounds are more readily perceived than constant noise sources (see, for example, PHYSICS TODAY, August 2013, page 19). Indeed, studies report that people are more likely to be annoyed by low levels of turbine noise than by much louder noise from transportation and other industrial sources. The degree of annoyance from turbine noise shows little correlation with the average sound level, termed the equivalent continuous sound-pressure level, yet that parameter is commonly used in noise regulations. To better understand the perception of turbine noise, Yeolwan Seong, Soogab Lee, and colleagues from Seoul National University have studied different ways of parameterizing the sounds. The researchers had test subjects in an anechoic chamber listen to simulations of wind-turbine noise at varying distances and orientations; for each sample, the subjects recorded their degree of annoyance on a seven-point scale. The team found that the listeners' responses were best explained statistically not by the average sound level or fluctuation level but by the maximum instantaneous sound level, a parameter frequently used in criteria regulating nighttime (and some daytime) intermittent noise sources. (Y. Seong et al., *J. Renewable Sustainable Energy* **5**, 052008, 2013.) —RJF

Taming topological defects with light. Real crystals are rarely perfect; they tend to contain the occasional defect, such as the one in the colloidal packing depicted here. The packing is visualized as a Voronoi diagram, with each 2-μm-diameter colloidal particle represented by a polygonal cell. In what's known as a dislocation, two extra rows of particles, indicated by dashed yellow lines, have been squeezed into the hexagonal lattice, leaving one particle (white) with only five nearest neighbors and another (gray) with seven. (For more on colloidal crystals, see PHYSICS TODAY, September 2010, page 30, and December 1998, page 24.) A form of topological defect, dislocations are common in both colloidal and atomic crystals. Understanding how they emerge and interact is key to modeling the kinetics of melting and of solid-to-solid phase transitions. But experimentalists have lacked the means to reproducibly control such defects in the lab. Now William Irvine (University of Chicago), Paul Chaikin (New York University), and their coworkers have demonstrated a way to manipulate colloidal-lattice dislocations using arrays of holographically generated optical traps. Dubbed topological tweezers, the arrays can capture dozens of particles simultaneously—each particle in its own potential well—such that clusters of particles can be pushed or pulled in unison. By strategically nudging selected clusters, the researchers can create, steer, and even induce fission of lattice dislocations.

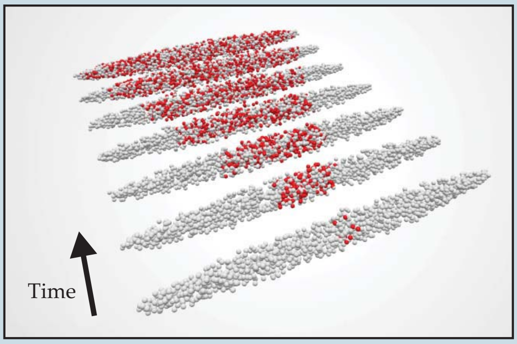


They can also rotate a cluster to create a grain boundary. But curiously, reversing the rotation doesn't return a pristine lattice; it only causes the boundary to expand. (W. T. M. Irvine et al., *Proc. Natl. Acad. Sci. USA* **110**, 15544, 2013.) —AGS

Exiting the heliosphere. As the Sun plows through the local interstellar medium (ISM), the wind of supersonic charged particles continually emanating from its surface envelops the solar system in hot, low-density plasma. Called the heliosphere, this plasma bubble is presumed to have a distinct aspherical boundary with the ISM's much cooler, higher-density plasma that comes within a few times 10^{10} kilometers of the Sun. (The orbital radius of Uranus is 5×10^9 km.) To considerable acclaim, NASA reported in September that its *Voyager 1* spacecraft, launched toward the outer planets 35 years ago, crossed that boundary "on or about" 25 August 2012, at a distance of 1.8×10^{10} km from the Sun. The principal evidence for the spacecraft's emergence into the ISM, the first by any human artifact, is the expected abrupt 40-fold increase in plasma density, measured by the rise of the plasma's density-dependent oscillation frequency. Simultaneous with the density step, *Voyager*'s cosmic-ray detectors recorded the abrupt disappearance of energetic charged particles from sources inside the heliosphere and a concomitant rise in the flux of cosmic rays from the rest of the galaxy. There was, however, one surprise.

Straightforward models of the heliosphere posit that its magnetic field, generated by the Sun, is quite independent of the galactic magnetic field beyond the bubble. But *Voyager's* magnetometer found no evidence of a change in the magnetic field's direction. The paper, authored by the team that monitors the spacecraft's plasma-wave detector, speculates that "the interstellar magnetic field may be linked to the Sun's magnetic field by some mechanism . . . not completely understood." (D. A. Gurnett et al., *Science* **341**, 1489, 2013.) —BMS

Equilibration of an isolated quantum many-body system. Despite extensive study, many gaps remain in our understanding of the statistical mechanics of quantum many-body systems. Among them is how an isolated quantum many-body system achieves thermal equilibrium. A new report by Jörg Schmiedmayer and colleagues at the Vienna University of Technology provides insights. A cigar-shaped, effectively one-dimensional ultracold gas of rubidium atoms provided a strongly isolated test system, intrinsically rife with fluctuations, that evolved on experimentally observable time scales. To probe its relaxation dynamics, the researchers split a trapped atom cloud longitudinally into two parts, let the resulting nonequilibrium state evolve for a certain time, then used matter-wave interferometry to measure the phase differences between the two parts along the length of the system. By conducting some 150 iterations for each wait interval, the team determined how the phase correlations between the two clouds evolved over time. Although the



split clouds started off strongly correlated (symbolized by gray atoms in this plot), the short-range coherence immediately began to decay exponentially with distance—a signature of thermal correlations (indicated by mixed red and gray atoms)—but only up to a certain length, beyond which long-range coherence persisted. Notably, the position of the crossover moved: The thermal correlations propagated through the system at the speed of sound. Technically, the phases relaxed to a so-called prethermalized state. Nonetheless, the results suggest a general route through which classical properties emerge in isolated quantum many-body systems. (T. Langen et al., *Nat. Phys.* **9**, 640, 2013. Image courtesy of the Vienna University of Technology.) —RJF

Making multifilament wires for electric solar wind sails. High-velocity protons stream copiously from the surface of the Sun. Harnessing their momentum for interplanetary travel is the goal of a novel propulsion system known as E-sail. Invented in 2004 by Pekka Janhunen of the Finnish Meteorological Institute, E-sail consists of long electrically conducting tethers that fan out from the spacecraft like the spokes of a bicycle wheel. Each tether consists of a web of interlaced wires, whose holes allow micrometeorites to pass through and whose electric field penetrates up to 100 m into the surrounding plasma. When protons encounter the positively charged tethers, they're deflected, and that generates thrust. Although the E-sail converts momentum efficiently, propelling a modestly sized spacecraft requires the tethers to be very long. To meet that criterion without overburdening the spacecraft with inertia, the wires must be very thin. In a new paper, a team led by the University of Helsinki's Henri Seppänen reports the culmination of a

four-year project to make an entire tether of micron-scale wires automatically. The prototype tether is 1 km long, consists of nearly 100 000 loops formed by three 25-µm-thick aluminum wires bonded to a 50-µm-thick base wire, and weighs just 10 g. The figure shows a typical section, with one loop highlighted in red. Making, checking, and repairing—if necessary—so many bonds entailed customizing a manual wire bonder and incorporating a microscope, image analysis software, and computer control. A shorter, manually produced E-sail is currently being tested aboard Estonia's first-ever orbiter, the tiny *ESTCube-1*. (H. Seppänen et al., *Rev. Sci. Instrum.* **84**, 095102, 2013.) —CD ■

issues and events

Japan's Fukushima site is an ongoing morass

The world-scale nuclear disaster needs to be addressed by world-wide expertise, critics say.

An underground cryogenic barrier is Japan's latest tack to stanch the flow of groundwater into the contaminated Fukushima Daiichi nuclear power plant. The plan has been met with criticism—as has much of the government's and the effectively nationalized Tokyo Electric Power Company's (TEPCO's) response to the multifaceted disaster brought on by the magnitude-9 earthquake and tsunami on 11 March 2011.

"They have got it wrong from A to Z," says Paris-based international energy consultant Mycle Schneider. "The wrong tanks [for storing contaminated water], the wrong materials, the wrong site preparation and monitoring. A big worry is that a new earthquake would destroy one or more tanks or a reactor building with its spent fuel pool and we'd get massive releases into the environment." The most pressing issues are dealing with the contaminated water—400 000 tons and counting—and ensuring that the reactor cores and the 15 093 fuel-rod assemblies onsite are kept under water. A failure to cool the fuel could lead to a buildup of decay heat, spontaneous combustion of the fuel cladding, and uncontrolled release of radioactivity.

Disaster zone

The six boiling water reactors at the Fukushima Daiichi power plant all suffered structural damage in the Great East Japan Earthquake and tsunami and the several reactor hydrogen explosions that followed. When backup generators flooded and failed, the cores of the three reactors that were working at the time melted through their primary containment vessels. Two and a half years later, some 400 tons of groundwater becomes contaminated daily as it flows into the site; pumping it out expands the onsite storage farm, currently around 1000 tanks, by two tanks every five days. And tons of radioactive water leaks into the Pacific Ocean each day. The government now admits this, says Mitsuhei Murata, a former ambassador to Switzerland. "And there is no immediate solution in sight."

At the time of the accident, Reactor 4 was down for maintenance, with spent fuel in its fourth-floor cooling pool. If that reactor collapses, says Murata, people would have to evacuate, "or die on the spot." The other two reactors were closed for refueling when the disaster struck. In September Prime Minister Shinzo Abe told TEPCO that like the others at the Fukushima Daiichi plant, they should be decommissioned. Extrapolating from the 1979 meltdown at Pennsylvania's Three Mile Island puts the decommissioning cost at about \$1 billion per reactor, according to Daniel Aldrich, a political scientist from Purdue University who has focused on nuclear power and disaster recovery for more than a decade. Others say it will cost more.

Remediation at Fukushima is much more complicated than the entombment carried out after the 1986 Chernobyl nuclear meltdown in Ukraine. "It's high time for a real consciousness about the level of complexity of this site," says Schneider. "It's not another Three Mile Island. It's not another Chernobyl. The difficulties go far beyond just a nuclear accident. It's a disaster zone."

TOKYO ELECTRIC POWER COMPANY

Standing atop Reactor 4 is a group from the US Nuclear Regulatory Commission during a visit last year to the Fukushima Daiichi nuclear accident site.

The complexity of the site on Japan's northeastern coast stems from the many unknowns about the conditions of the reactors; the risk of further fallout if a strong enough earthquake, tornado, or fire occurs or the power goes—as when a rat gnawed through a cable last March; and the discharge of radioactive water into the Pacific Ocean. Untrained laborers are recruited to clean up and monitor the site. "The most dangerous characteristic is that you don't know where the hot spots are," says Schneider. He recounts stories of people shielding their dosimeters to extend their employment and of workers in raincoats fastening bolts near toxic gushing tank leaks.

"Human error"

Add to that the host of humanitarian problems that have arisen in the wake of the accident: Tens of thousands of evacuees remain in temporary lodgings; farmers and fishermen can no longer make a living because people are wary about contamination from fish and from land crops; people worry about the possibility of developing illness from exposure to radioactivity; in areas where the radioactivity is elevated but not enough to get government assistance, people are scared to stay but have nowhere to go. Suicide, divorce, and depression rates have risen in communities affected by the disaster, says Aldrich.

"The area was not prepared ahead of time. The evacuations were done poorly. The government and TEPCO do not share information with the public. Communities have been destroyed. The Fukushima site has been mismanaged," says Aldrich. "These are all layered problems. And the base anxiety is related to them. The earthquake and tsunami were beyond human control, but what has happened since is human error."

The physical and technical complexities are exacerbated by the management of the remediation, which so far has been TEPCO's responsibility, and by the breakdown of public trust in TEPCO and the government. In his research, Aldrich found that public trust in the government and national authorities plummeted from 85% in 2010 to 8% some three months after the March 2011 disaster. The distrust is the "biggest problem," says Schneider. He and others note that it's unrealistic to expect TEPCO, a utility company, to have the know-how to deal with a nuclear accident.

"My complaint is that TEPCO should have overdesigned," says Dale Klein, chair of a five-member committee that advises the company on nuclear safety. "Their safety assessments should have been more robust. A few years ago, their own engineers said a hypothetical tsunami could be 16 meters high—the tsunami [on 11 March 2011] was 14 meters. They should have thought about what they would have done if hit by a larger-than-expected tsunami—things like making watertight battery compartments."

"I am advocating that TEPCO create a special unit only charged with decommissioning," says Klein, a former head of the US Nuclear Regulatory Commission. He also agrees that communication needs to be better: "TEPCO presents information without context. A lot of good work they are doing gets buried when they have poor communications and misinformation."

Remediation

In early September the Japanese government announced that it would foot the bill for an ice wall and water filtration equipment proposed by TEPCO. Pipes to carry cooling fluid will be installed underground to freeze the soil and keep groundwater away from the four damaged reactors. The ice wall will be roughly 1.5 km long and up to 30 m deep. A decision on the final depth will be based on the results of geological surveys and other tests, says Hirokazu Yamaguchi, TEPCO general manager of corporate reform. "We will confirm that the soil can be frozen to bedrock by conducting operation tests."

At an estimated $320 million, the ice wall is about a third to half the cost of a subterranean steel barrier that was rejected earlier as too pricey. Of the options considered by TEPCO and the government, says Tatsujiro Suzuki, vice chairman of the Japan Atomic Energy Commission, "ice is the fastest, [initially] cheapest way to stop the water, but it's only been used on a small scale." A prototype will get under way soon, he says. "They think this is almost zero-percentage penetration. But they have already started thinking about backup plans." Critics note that even if the technique works on the large scale, vast amounts of electricity will be needed to keep the soil frozen. "It can't be a permanent solution," says Murata.

The filtration system will cost about $150 million and will remove the radioactive isotopes of cesium, strontium,

PEACE BOAT

Protesters demonstrate against nuclear power in Yokohama, Japan, in January 2012.

and other elements from water. Tritium cannot be removed.

This month TEPCO begins moving the spent fuel from Reactor 4 to a ground-level common pool. Transferring all 1533 assemblies is expected to take about a year. Later, the fuel will be put in dry casks of concrete and steel for long-term storage.

Global wisdom

In mid-August TEPCO revealed that a storage tank had spewed out 300 tons of contaminated water—about one-eighth the volume held by an Olympic swimming pool. It was not the first leak, and it's impossible to know exactly how much escaped or where it went; moreover, many of the water storage tanks are bolted, not welded, together, and the vast majority do not have volume gauges installed. A few weeks later Abe assured the International Olympic Committee that the Fukushima site is "under control"—and Japan won its bid to host the 2020 summer Olympics. That claim was followed by a seemingly contradictory statement by TEPCO. Such events have put a new spotlight on the crippled Fukushima nuclear site. "The renewed attention is where I am a bit hopeful," says Schneider.

"The only tiny little blinks of good news were a couple of statements about needing international advice. But for the time being, the result is zero—the international input they are announcing is either bilateral or individual. This is far from good enough," he says. To be sure, the Japanese government and TEPCO have consulted experts from outside the country. But, says Schneider, "If they bring in only people that are perceived as nuclear proponents, that is a problem. For technical issues, I don't care whether the experts are pro nuclear or not. But there needs to be expertise that is independent of state and corporate interests." He first floated the idea for an international task force in 2011, just weeks after the accident. But, he says, "you cannot push from the outside if no one pulls from the inside."

"The government should get more involved, and should create a system to utilize global wisdom for the site," says Suzuki. "Unfortunately that process seems slower than expected."

"The nuclear accident cannot be solved by a single state or company," says Murata. "If the world does not learn the lessons of Fukushima, this tragedy will take place again." Still, he points to a few positive developments. The formation last year of the Nuclear Regulation Authority as a separate government body may lead to better oversight of nuclear power plants. And an official at the Ministry of Economy, Trade and Industry shares the "sense of crisis," says Murata. "Many ideas are sleeping. If a real task force is established, the Fukushima crisis will become more manageable."

Klein says he "would like to see the Japanese government have a robust monitoring system so the public can feel assured and trust that their fish supply is safe. They need a massive educational program to convince people that it's okay to eat the fish." Based on his involvement with Fukushima, he adds, "I have no problem eating fish when I am in Japan." But South Korea, for example, recently announced that the country will not import fish from certain areas of Japan.

Japan's nuclear future

Not surprisingly, a majority of Japanese citizens want to phase out nuclear power. But in a reversal from the previous government, which was in charge at the time of the Fukushima accident, the current Abe government favors nuclear power. Restarting nuclear reactors is a higher priority than cleaning up the Fukushima site, critics say. Playing into the discussion about the future of nuclear power in Japan is debate over whether the meltdowns at Fukushima were caused by the earthquake or the tsunami. For nuclear power proponents, the tsunami is the more comfortable answer, since huge tsunamis are rarer than large earthquakes.

Last year saw the launch of Mayors for a Nuclear Power Free Japan. The group now has nearly 90 members, some from areas near the Fukushima site, where economies have traditionally depended on the nuclear power plants. "If this body continues to grow," says Akira Kawasaki of the activist group Peace Boat, "it will have good political and even financial power to counter measures by the national government."

Pressure continues to mount: In early October, former prime minister Junichiro Koizumi announced that he now opposes nuclear power. And his son Shinjiro Koizumi, who has criticized the handling of the March 2011 disaster and is an advocate for its victims, was recently appointed one of four parliamentary secretaries in charge of reconstruction.

According to Aldrich, it's unlikely that Japan will phase out nuclear power. But given public opposition, he predicts that "four to seven reactors will be as good as it gets." Before the Fukushima disaster Japan had around 50. Kawasaki notes that Tokyo survived the hot summer without nuclear power. "The case that Japan needs plants is not persuasive anymore," he says. The government is due to submit a broad energy policy by the end of this year.

Toni Feder

Geoengineering researchers ponder ethical and regulatory issues

With interest in artificial climate intervention heating up, advocates and foes agree on the need for a governance regime to sanction experimental trials.

As part of a research project exploring stratospheric particle injection to possibly mitigate global warming, a team of UK scientists and engineers in 2011 readied an experiment to spray water through a hose tethered to a balloon 1 km above Earth's surface. Although the experiment's environmental impacts would have been nil, leaders of the research ultimately called it off.

In 2012 the indigenous Haida people of British Columbia contracted to dump 100 metric tons of iron sulfate into waters off the west coast of Canada in hopes of stimulating phytoplankton growth and restoring a salmon fishery. Such ocean fertilization also has been proposed for removing and sequestering atmospheric carbon. But the practice is banned by the London Protocol on ocean dumping.

As discussion of geoengineering—the deliberate intervention in Earth's climatic system to mitigate global warming—moves from the fringes of science to serious consideration as a possibly last-resort solution, such ethical quandaries are expected to proliferate for experimentalists. The Intergovernmental Panel on Climate Change, in its Fifth Assessment summary for policymakers released on 27 September, mentions geoengineering for the first time. It warns that solar radiation management—the injection of reflective particles into the atmosphere and arguably the most controversial geoengineering approach (see PHYSICS TODAY, February 2013, page 17)—could alter the global water cycle and would do nothing to slow ocean acidification.

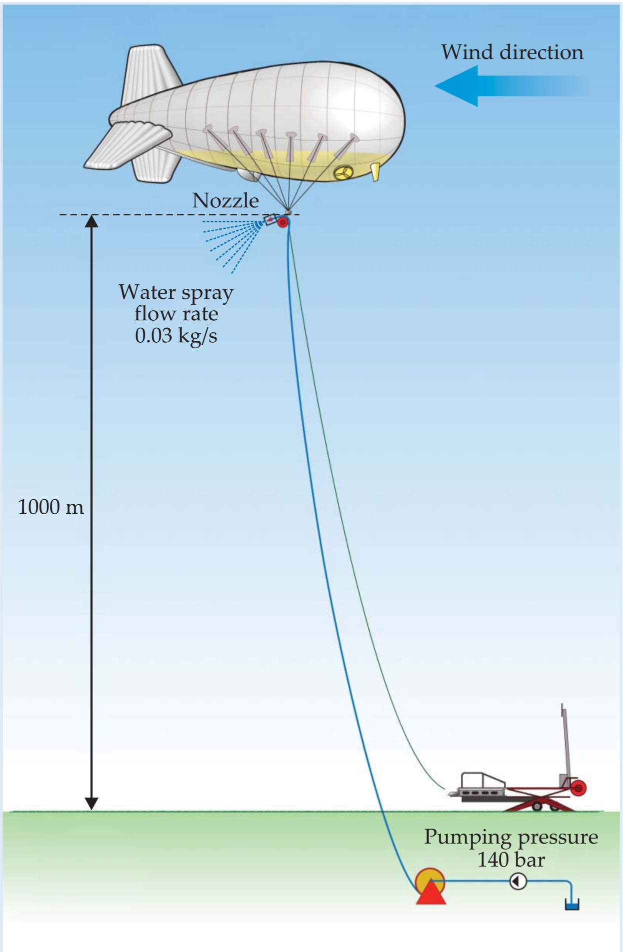
Although debate has arisen over who decides whether geoengineering technologies will ever be deployed, the more urgent issue for researchers is the sanctioning of outdoor experiments that must occur long before deployment. Because of the inherent risks of adverse impacts, agreement is widespread, even among geoengineering's strongest proponents, that some sort of governance for such tests is needed.

A slippery slope

No national or international governance for geoengineering experiments currently exists, and not surprisingly for such a controversial subject, no consensus has emerged on the form it should take. Some organizations, such as the ETC Group, an environmental organization based in Ottawa, Canada, argue for a ban on all outdoor experimentation. But geoengineering researcher David Keith of Harvard University and others advocate a voluntary code of conduct that would only have to be adopted by a handful of funding agencies in the US, Europe, and Asia.

"There are legitimate fears of a slippery slope, and there is a fundamental lack of regulation," Keith said at a September meeting of a National Research Council (NRC) committee that is assessing geoengineering research. "If someone really wanted to put large amounts of sulfur into the stratosphere over the US, it's not obvious what regulations would bind," he warned. The Clean Air Act doesn't apply because, for one thing, it regulates only fixed emissions sources, and the Kyoto Protocol doesn't apply because sulfur is not on its list of greenhouse gases. Federally funded experiments in the US could require an environmental assessment first, but no such restriction would apply to privately financed experiments. The lack of restrictions will create perceived—and possibly real—problems if large experiments do proceed.

In its 2009 report *Geoengineering the Climate: Science, Governance and Uncertainty,* the UK's Royal Society called for international scientific organizations to join in developing a code of practice for research and a voluntary research governance framework. The UK House of Commons Science and Technology Committee and the US House Committee on Science, Space, and Technology cooperated on geoengineering investigations that produced reports in 2009 and 2010. Both endorsed the Oxford principles, a set of five conditions drafted by a team of scholars, under which geoengineering research should be allowed to proceed. Those principles state that research should be regulated in the public interest, public engagement should be sought in the decision making, the research results should be publicly disclosed, the results should be independently assessed, and robust governance structures should be in place before any geoengineering technology is deployed.



HUGH HUNT, UNIVERSITY OF CAMBRIDGE

A UK experiment dubbed SPICE (stratospheric particle injection for climate engineering) would have tested a method for injecting aerosols into the upper atmosphere through a 1-km-long pipe attached to a tethered balloon. It was canceled due to concerns over the lack of governance for geoengineering experiments.

Steve Rayner, a political anthropologist at Oxford University and an author of the principles, says the degree and formality of governance should vary with the severity of the potential side effects. "If you were talking about sulfur aerosols in the atmosphere, it would seem that unless you were up for a great deal of international conflict, it's not something you would do without an international agreement," he says. On the other hand, the planting of trees to serve as a carbon sink could be reasonably governed with existing planning and environmental protection laws.

Many approaches

Keith has proposed that NSF and a few other funding agencies, such as the European Research Council and the Chinese Academy of Sciences, develop a nonbinding memorandum of understanding (MOU) spelling out how they propose to evaluate experiments. Terms might include independent risk assessment, transparency, and degree of usefulness. Only a handful of agencies would need to sign the agreement, Keith said. "An MOU like that would tend to bind the research of even agencies that didn't sign it," he explained to the NRC committee, since other, nonsignatory funders would look to the MOU for guidance in reviewing research proposals they may receive.

Other parties argue for a more formal system of governance. Although his organization hasn't backed a particular approach yet, Mark Lawrence, scientific director of the Institute for Advanced Sustainability Studies in Potsdam, Germany, says that an international governance framework should be put in place before any field experimentation is done. "Our deep concern is with the potential for backlash and how that may hinder future basic science," he says.

Scott Barrett, a Columbia University economist, advocates for an international agreement under the auspices of the United Nations (UN). But the regime can't be so heavy-handed that it loses participation from countries that are in a position to do geoengineering, he told the NRC panel. He added a note of realism: "The idea that people are going to spend a lot of effort and go right to high-level laws on things that aren't happening and may not ever happen is kind of naive."

Barrett disagreed with hardliners who argue that no geoengineering research should be done. "Do you really want to do nothing until we're in a very, very tight situation, and is it really plausible to think that you're going to get 193 countries to do nothing about this through an international agreement?" he asked.

To an extent, the ethical situation facing geoengineering is analogous to the advent of recombinant DNA technology in the mid 1970s. In that case, scientists agreed to an international moratorium on gene-splicing research until a code of conduct on biosafety, now known as the Asilomar principles, was developed. In the US, the National Institutes of Health created a committee of external advisers to review the safety and ethical issues involved with grant proposals involving rDNA. David Winickoff, an ethicist at the University of California, Berkeley, told the NRC panel that a geoengineering advisory committee could review experimental proposals, ensure public disclosure and access to results, perform annual reviews of the science, and reach out to other nations' governance bodies.

Lawrence thinks a likely scenario is for the scientific community to develop a code of conduct that will be administered by an international organization—perhaps the UN Framework Convention on Climate Change or the international Convention on Biological Diversity—or, alternatively, that will be adopted by the funding agencies of the research-funding nations.

Matt Watson, who heads the research project SPICE (stratospheric particle injection for climate engineering), which had planned to spray water from the tethered balloon, disputes news reports that blamed public opposition for cancellation of the experiment. A small element of the overall research project, the experiment was delayed to the point where it became less useful, he says. "From the standpoint of someone who was about to conduct an experiment that had absolutely no climate signature whatsoever, I would argue that a level of preexisting governance would have helped that experiment," he says. "We were going to make sure it was safe and very well communicated and legal. But we thought it might be used by other people to legitimize outdoor research that everybody would be uncomfortable with."

Watson favors strong international governance and says that it must include representation from outside the US and Europe. The governing body he foresees would register experiments, ensure the transparency and communication of the results, and review proposals for scale and possible adverse effects.

Negligible impacts?

A key point of division in the governance debate is over whether outdoor experiments below a certain size should be allowed to proceed without approval. Keith, a proponent of such a threshold, has proposed an experiment that would deliver 1 kg of sulfur and 100 kg of water by balloon into the stratosphere and observe the effects. He says the experiment could help inform models that predict whether stratospheric sulfate injection could keep Earth's temperature within safe levels. Keith suggests that his experiment is sufficiently small, as measured by its estimated annual impact on radiative forcing, to be allowed to proceed without a specific ethical review.

But others interviewed say there should be no threshold level for experiments. Watson, for instance, agrees that Keith's experiment would be inconsequential climatologically and its effects so small that he would have trouble even detecting them. But, he says, "the social impacts and the reverberations around undertaking that experiment are significant. I don't know if they can or should be predicted or managed." Intentions are very important, he says; if the experiment was labeled as something other than geoengineering, no one would care. He points to a 2011 experiment on cloud microphysics that was performed off the coast of Monterey, California. Although much larger in scale than SPICE and having what Watson says was "a profound effect on the local climate," the experiment created no public stir because few people realized at the time that it was related to geoengineering. "People release atmospheric tracers for experiments all the time, but because it's about atmospheric chemistry and looking at weather systems, nobody would ever object to them."

Lawrence argues that potential backlash from even very small-scale experiments involving solar radiation management could threaten research in noncontroversial areas of atmospheric research as well. He notes how the 2012 ocean fertilization incident off Canada may influence the changes being made to the London Protocol that will make it difficult for non-climate-related research on surface water nutrient cycling to proceed. The 87 countries that are parties to the protocol agreed in 2010 to ban ocean fertilization for other than scientific research purposes; they also established a framework for assessing such experiments that does not include a threshold.

David Kramer

Breaking from tradition, some scientists self-publish

Online platforms offer more control over the publishing process, but no editorial peer review.

Earlier this year, University of Michigan condensed-matter physicist Leonard Sander sent out a mass email promoting his new textbook. "I published this book using [the online self-publishing platform] CreateSpace (a subsidiary of Amazon)," he wrote. "One reason for this choice is the out-of-control inflation of textbook prices. The downside of this publishing method is that the marketing offered by a publishing house is not available, hence this email."

Sander's choice is not common. The self-publishing route is more typically taken by aspiring novelists looking for a breakthrough or by amateur scientists peddling rejected theories. But for every *Fifty Shades of Grey*—the best-selling, originally self-published romance novel—there are thousands more self-published books that barely make a dime. And for every professional scientist who experiments with self-publishing, there are several more pseudoscientists who are publishing for validation.

***Blazing the Trail* coeditor** and Yale University PhD physics student Emma Ideal signs copies of the self-published book at the 2013 SACNAS conference—SACNAS is a society for the advancement of Hispanics and Native Americans in science.

Although most scientists with established or budding reputations continue to opt for traditional publishing, a few are giving self-publishing a shot. For Sander, the ability to manage the overhead costs and make his book more affordable for students was reason enough. At $42, the list price for *Equilibrium Statistical Physics with Computer Simulations in Python* is about half what he estimates a traditional publisher would have charged.

The self-publishing industry claims other benefits. For example, says Amazon.com spokeswoman Brittany Turner, CreateSpace lets authors "keep control, publish quickly, publish for free, publish globally, and earn more money." On many self-publishing platforms, authors can take home up to 50% in royalties from print sales and up to 70% from ebook sales; the typical royalty rate for academic publishers is 10–20%.

$1 per error

Despite having a poor, lingering reputation as a modern form of the vanity press, self-published books sell. "Over a third of the top 100 best sellers on Kindle [Amazon's ebook platform] in September were [self-published] titles," says Turner. (None of the best sellers were serious books on science.) And from 2006 to 2011, the period when a number of online self-publishing platforms launched, the annual production of self-published titles tripled, according to a 2011 report from Bowker, the official US agency that grants ISBNs.

Depending on the platform, authors pay little or nothing and do the entire layout, editing, and marketing, or they hire freelancers to do that work for them. Even when submitting to traditional publishers, "you write the book, you typeset it, you make the figures, and you send them the PDF," says physicist Mark Newman, Sander's colleague at the University of Michigan, who self-published his own 2012 textbook, *Computational Physics* after traditionally publishing his previous seven books. "[They mainly] copyedit it and handle the sales and marketing."

But what traditional publishers also offer is "the gatekeeping—useful, independent feedback," says Simon Capelin, editorial director for physical sciences at Cambridge University Press, which published Sander's previous textbook. "The production of the book is the cheap and easy part." For prepublishing feedback, both Sander and Newman sent their manuscripts to colleagues; Sander also offered the students taking his statistical physics course a dollar for each misprint they found. Both professors say their self-publishing was "an experiment"; Newman says that his book has been adopted by several physics departments, so "I feel like [the experiment] has been a reasonable success."

Textbook prices have skyrocketed in the freshman physics category, because they demand a lot of marketing and because the used-books industry has undercut profits from their sales, says Capelin. Cambridge University Press does not compete in that category, he adds, but publishers that do, like Cengage Learning, have explicitly stated that their long-term business strategy is to transition from print to digital educational and research materials. "When Amazon first started up, I couldn't imagine that they would have essentially replaced traditional bookstores," says Capelin. "I don't know that [online self-publishing] will have a similar impact on academic publishing, but I may be proved wrong."

Blazing a trail?

Capelin says he encourages authors of some rejected manuscripts to try self-publishing, which transfers the publishing risks and the marketing costs to the author and offers feedback in the form of sales. That's what theoretical physicist Teman Cooke did after being turned down by Cengage. His book, *The First Semester Physics Survival Guide: A Lifeline for the Reluctant Physics Student*, details a pedagogical approach he says he developed in seven years of teaching introductory physics courses at Georgia Perimeter College in Atlanta. Cooke says he used $6000 that he raised on the crowdfunding site Kickstarter.com to hire copyeditors and marketing consultants. "It would be awesome if [the book] pulls income," he says, "but I just want to see if [my pedagogy] works." He recently formed his own company to help other authors navigate the self-publishing process.

While in South Africa for the 2011 International Conference on Women in Physics, graduate students Emma Ideal and Rhiannon Meharchand learned about a book of essays by prominent women scientists in India and were inspired to produce a similar book featuring women scientists in the US. When they approached Yale University Press, however, the publisher didn't warm to the idea, says Ideal, a student at the university.

So the pair decided to try self-publishing. This summer they finished their book, *Blazing the Trail: Essays by Leading Women in Science*, which features 35 essayists, most of them physicists. Using funds donated by their graduate physics departments, Ideal and Meharchand—who attended Michigan State University and is now a postdoc at Los Alamos National Laboratory—send out copies of their book to various science departments, science associations, and libraries. Although the writing and editing process took almost two years, Meharchand says that with a traditional publisher, the process would likely have taken even longer and the essays may have been subject to overediting. "We had control of the speed of production and control of the message," she says.

But Audra Wolfe, a former acquisitions editor for Rutgers University Press and now an independent publishing consultant, sees only a limited role for self-publishing in science. "An effective use of self-publishing may be if you have a fairly technical book—for example, conference volumes—and you know how to reach your target audience," she says. "But hardly any [news publication] will review a self-published book, and it won't get you tenure. As long as scholars care about credentials, I think there will be something resembling the traditional publishing industry."

Jermey N. A. Matthews

NNSA touts savings from supercomputing

Nuclear weaponeers look toward exascale computing, but major breakthroughs in power consumption, handling of massive data sets, and other areas are needed first.

Recent advances in computational capabilities are cutting as much as $2 billion off the cost of refurbishing and maintaining the US nuclear weapons stockpile, say officials of the National Nuclear Security Administration (NNSA). Now the weapons program has set its sights on exascale computing—three orders of magnitude faster than the current state-of-the-art petascale computers—by around 2020.

Increasingly powerful simulations have contributed to decisions in recent years to use recycled plutonium pits instead of newly manufactured ones in the life-extension programs for several aging weapons systems. Those decisions in turn led the NNSA to postpone construction of a new pit production plant at Los Alamos National Laboratory for at least five years. And simulations recently helped officials determine that a "very expensive" proposed warhead modification wasn't actually needed to correct a problem in one weapons system, says Donald Cook, the NNSA's deputy administrator for defense programs.

Exascale computing will allow modelers to simulate with a much finer degree of granularity what happens with weapons components, Cook says. "If you look at the granularity of metals, plastics, and polymers, the limitation on computing now is that . . . you have to make in the assumption that the material behaves kind of uniformly down below a certain size level." Current simulations can't account for grain boundaries in metals, he notes. "Yet if you look at where cracks develop in metals they always develop at the grain boundary. If you look at where corrosion occurs, it's at a grain boundary. If you look at the effect on materials of aging, you gather a lot of chemical contaminants at the grain boundary."

Billion-dollar impacts

Dimitri Kusnezov, a senior adviser to Energy secretary Ernest Moniz, told the Secretary of Energy Advisory Board on

13 September that simulations performed this year had helped determine that the lifetime of a particular weapons system is a decade longer than it was believed to be just two years ago. Kusnezov said that the simulations to produce the finding were not available two years ago and that the finding would save the NNSA $2 billion. "Today we make decisions with [billion-dollar] impacts that we could not do just 2–3 years ago," he stated in his presentation. Cook says the savings achieved with simulations have already been incorporated in the NNSA's budget request and outyear projections. "It's not like there was a discovery and all of a sudden we knocked $2 billion off the cost of everything," Cook says.

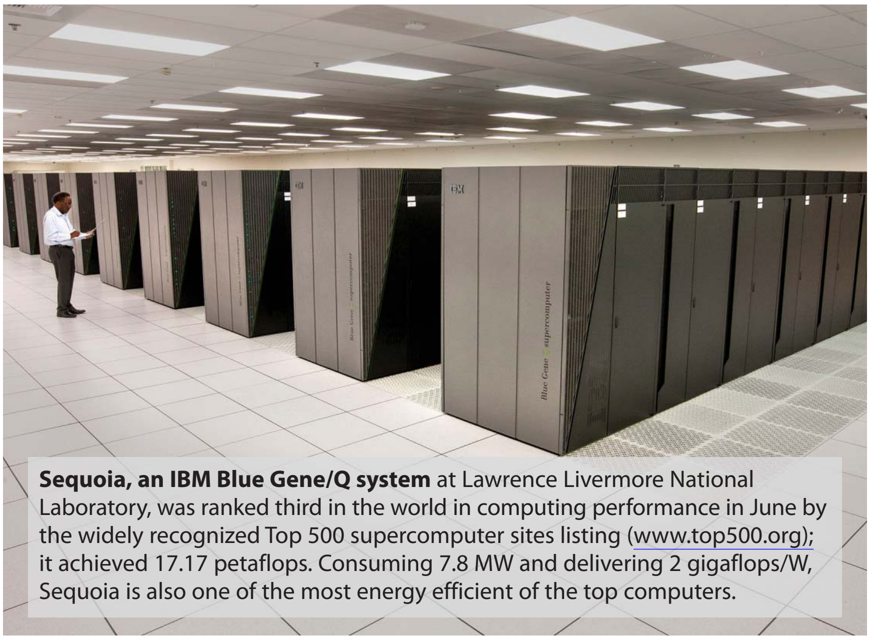
Pit reuse has been approved by the NNSA for the refurbished W76, a warhead carried by Trident missiles; for the B-61 bomb; and for the proposed integrated replacement for the W78 and W88 warheads carried by Minuteman land-based and Trident missiles. Further savings would result if the NNSA decides, as is likely, to reuse pits in life extension of W80 warheads carried by air-launched cruise missiles, Cook says.

Based on simulations and experimental results, researchers at Lawrence Livermore and Los Alamos National Laboratories reported last year that pits should function as designed for at least 150 years. That's up from the 85-year minimum pit life the two labs had estimated in 2006.

Keeping cost growth down

But even with pit reuse, the estimated cost of the B-61 life extension has soared to $10 billion, according to a Department of Defense assessment. That's up from the $4.5 billion estimated just two years ago, before the NNSA and the DOD decided to add more features to the refurbished bomb. Senate appropriators have balked at the increase; their version of a fiscal year 2014 funding bill would cut the NNSA request for the B-61 program. Although House appropriators added to the B-61 request, they, too, expressed concern over its high cost and ordered the NNSA to better justify the program. At press time, FY 2014 appropriations were unresolved.

Still, modeling helps prevent further cost growth on the B-61 program, Cook says. He points to two tests, carried out by engineers at Sandia National Laboratories in August, of the pulsed Doppler radar developed to replace the bomb's existing vacuum-tube version. Neither the full set of data obtained in each test nor Sandia's decision that further tests



LLNL

Sequoia, an IBM Blue Gene/Q system at Lawrence Livermore National Laboratory, was ranked third in the world in computing performance in June by the widely recognized Top 500 supercomputer sites listing (www.top500.org); it achieved 17.17 petaflops. Consuming 7.8 MW and delivering 2 gigaflops/W, Sequoia is also one of the most energy efficient of the top computers.

are not required would have been possible without modeling and simulation, he says.

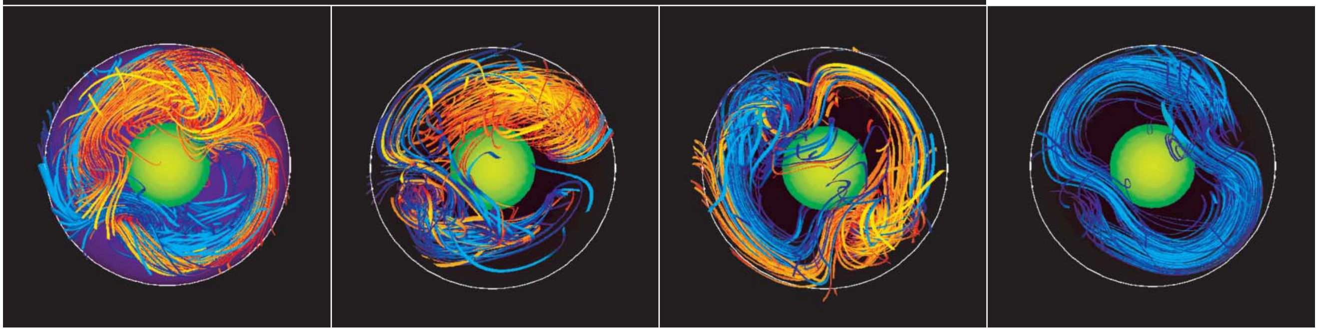
"Simulation is a great boon, but without experiments, you wouldn't know what to trust in the codes," says Cook. "So it's a combination where we're using simulations to drive the kind of experiments that we're doing in order to benchmark the simulation."

Within the limits of reasonable power consumption, which the NNSA defines as 20 MW or less, there is no obvious path to exascale computing, Kusnezov told the Secretary of Energy Advisory Board. A 1-teraflop Intel microprocessor the size of a pack of gum—equal in processing speed to the world's most powerful supercomputer in 1996—is expected to come on the market within two years, he said. But an exascale machine would require 1 million of them. New programming paradigms, new methods for dealing with massive data sets up to the yottabyte (10^{24}-byte, or trillion-terabyte) scale, and new programming paradigms, said Kusnezov, are among the challenges that will need to be overcome.

David Kramer ■

THE GEODYNAMO'S unique longevity

Peter Olson



New insights into how Earth's magnetic field has been sustained for billions of years closely link the planet's core and mantle in the dynamo process.

Exploration of the solar system has confirmed that most of its planets have magnetic fields. Although the planets differ in important details, the reason they are magnetic is fundamentally the same: In each planet, a self-sustaining dynamo has operated at some time in history. In such a dynamo, electric currents and magnetic fields are continuously induced by motions of conducting fluid inside the planet.

The evidence for self-sustaining dynamo action throughout the solar system—Venus may be the lone planetary exception—is not surprising because only three basic ingredients are needed: a large volume of electrically conducting fluid, planetary rotation, and an energy source to stir the fluid. Planets generally acquire all three in abundance during their formation. Indeed, dynamo action is not limited to the planets; it produces the 11-year solar cycle,[1] and evidence exists for dynamo action in the Moon, in some of the Galilean satellites, and even in meteorite parent bodies.[2]

More puzzling, however, is the fact that other terrestrial (that is, solid) planets and satellites failed to sustain dynamo action for very long. In Mars and the Moon, the record of remnant crustal magnetization points to dynamo cessation within a few hundred million years after their formation.[3] The geodynamo, on the other hand, managed to locate a fountain of youth that its sibling planets had missed, and it is still going strong. (Earth is 4.54 billion years old.) The geomagnetic field intensity is actually greater today than at most times in the past, even though its intensity happens to be rapidly decreasing at the moment. Furthermore, over the past 5 million years, the geomagnetic field has reversed polarity at near-record rates, a sure sign of vigor.

What accounts for such stark differences in the dynamo histories of otherwise similar planets? Both Mars and Venus rotate and have large metallic cores, comparable to Earth, so the answer is not likely to be found in those features. Instead, it appears that Earth's core has tapped into a much larger reservoir of energy, sufficient to power the geodynamo for billions of years, with no end in sight. The cores in some other terrestrial planets were forced to operate on far leaner energy budgets, and rather quickly those budgets proved too austere.

Heating and cooling

Current models of solar-system formation emphasize the important influence of large impacts on the initial structure and state of the terrestrial planets and on the process of core formation,[4] which is likely when dynamo action began. Giant impacts are thus a good place to look for the source of differences between terrestrial planets. The impacts produce copious melting and allow core-forming metals (mainly iron and nickel) to quickly and efficiently segregate from mantle-forming silicates within superheated magma oceans. (See the article by Bernard Wood, PHYSICS TODAY, December 2011, page 40.)

That scenario applies particularly well to early Earth in light of the hypothesized impact of a Mars-sized object that produced the Moon (see the article by Robin Canup, PHYSICS TODAY, April 2004, page 56). Earth's newly formed core would have been very hot—well over 5000 K and totally molten—

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replete with lighter elements such as oxygen, sulfur, silicon, and perhaps magnesium and carbon. As Earth's core cooled over geologic time, its composition necessarily changed. The iron–nickel mixture that makes up most of the core likely became saturated with respect to the least-soluble light elements; those accumulated at the top of the core and possibly became incorporated into a remnant magma ocean at the base of the overlying mantle, as illustrated in figure 1.

The dense residual liquid metal, partially depleted of lighter elements, sank back into the core and in doing so produced the motions needed to induce the electric currents for the early geodynamo. The duration of that first stage of the dynamo's evolution is unknown, but it may well have lasted several billion years. With additional cooling, the liquid metal in the core eventually reached its solidification temperature. Solidification probably started at Earth's center: The melting temperature of iron-rich alloys increases so rapidly with pressure that most terrestrial cores are expected to freeze from the inside out. With solidification, Earth's core entered a second phase of evolution. And further cooling has led to the progressive growth of the solid inner core to its present size—the final major step in the construction of our modern planet.[5]

According to the above model, the solid inner core forms rapidly and therefore may be relatively young. The present-day heat loss from the entire core is uncertain, but best estimates[6] place it in the range of 10–16 TW (by comparison, the total heat loss from Earth's interior—crust, mantle, and core—is approximately 46 TW). The solidification rate of the inner core is thus about 6000 Mg/s if we ignore radioactive heat sources. Extrapolating backward in time to first nucleation, the predicted age of the inner core is less than 1 billion years, far younger than Earth itself. Only a large dose of radioactive heat in the core—the isotope potassium-40 being the most likely source—would prevent the inner core from solidifying so quickly.

An important property shared by both evolutionary stages in figure 1 is that the gravitational potential energy of the core decreases. As described in the companion article by Bruce Buffett on page 37, that release of gravitational potential energy and its conversion to kinetic energy of fluid motion are primarily what has sustained the geodynamo over its long history. During the first stage, the density of the core increased by thermal contraction and the loss of insoluble light elements. During the second stage, which is ongoing, thermal contraction continues. But more importantly, soluble light elements are being concentrated in the liquid outer core and depleted from the solid inner core. The result is that the density of the outer core drops while the density of the inner core rises. In both stages, the partitioning of light elements leads to unstable stratification, which produces in the fluid convective motions that redistribute the light elements and lower the gravitational potential energy of the core as a whole. Ordinary electromagnetic induction then converts part of the kinetic energy of fluid motion into electromagnetic (mostly magnetic) energy, which completes the dynamo process.

Alternative energy sources—for example, instabilities produced by Earth's precession and tidal forces—may contribute additional power. Radioactive heat sources may also contribute to the overall energy balance in the core. But the gravitational dynamo mechanism is thought to provide most of the power for the geodynamo,[7] and accordingly, the future of the geodynamo is particularly bright. As of today, only about 4% of Earth's core has solidified, so there is plenty of energy remaining to sustain the geomagnetic field for hundreds of millions, if not billions, of years to come.

The mantle matters

Why then has the dynamo process not been sustained in other terrestrial planets? The probable answer lies beyond the dynamo region in the solid silicate mantle that surrounds the metallic core of each planet. Earth's mantle is unique among terrestrial planets in that it supports a global system of plate tectonics. The creeping flow of the silicate material associated with plate motions overturns Earth's

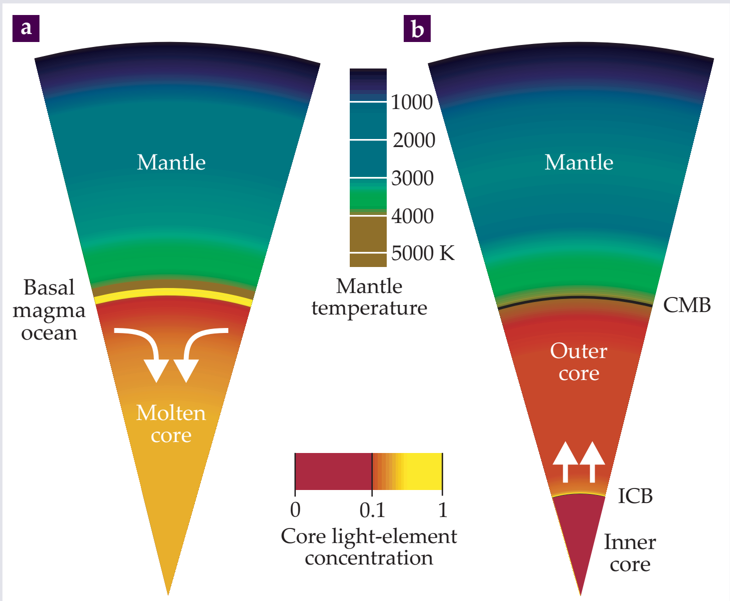


Figure 1. Evolution of Earth's core. As Earth's interior cooled following the planet's accretion, two distinct convective energy sources for powering the geodynamo emerged. **(a)** Early on, Earth's core was hot enough to be entirely molten, with a magma ocean at the base of the lower mantle that absorbed low-solubility light elements from the nearby core. During this stage the geodynamo was driven mostly by the sinking of newly dense fluid produced near the top of the core. **(b)** As Earth cooled, the core's center began solidifying. As it did so, the growing inner core expelled more soluble light elements into the molten outer core. During that stage, still ongoing, the core–mantle boundary (CMB) is nearly impermeable and the geodynamo is driven mostly by buoyancy produced at the inner-core boundary (ICB).

mantle on time scales of tens of millions to hundreds of millions of years. The flow efficiently draws heat off the core–mantle boundary and transports it to the surface within giant upwellings and plumes. Without the heat transport provided by mantle flow, the cooling rate of Earth's core would be vastly reduced, and so would be the strength of the dynamo mechanism.

It's an open question why plate tectonics are absent from other terrestrial planets. According to one hypothesis, mobile plates require water-filled oceans because water weakens mantle rocks and plate boundaries (see the article by Marc Hirschmann and David Kohlstedt, PHYSICS TODAY, March 2012, page 40). Another hypothesis is that surface temperature controls plate formation.[8] In any case, without mobile plates—and in particular, without plate subduction—mantle overturn is weak, intermittent, or nonexistent. Consequently, long-term sustainable dynamo action in a terrestrial planet without subduction becomes uncertain.

The criterion that best distinguishes a sustainable fluid dynamo from an unsustainable one is the magnetic Reynolds number *Rm*. An often-used definition of that parameter is $Rm = \mu\sigma ud$, where μ is magnetic permeability of the fluid, σ is its electrical conductivity, u is the root-mean-squared fluid velocity, and d is the depth of the dynamo region. In physical terms, *Rm* is the ratio of two fundamental time scales: the decay time of electric currents due to ohmic resistance in the fluid divided by the characteristic time for fluid circulation. Dynamo action requires a large *Rm*. However, that can be achieved in multiple ways. For example, laboratory dynamos reach large magnetic Reynolds numbers using high fluid velocities, whereas planetary dynamos reach them by virtue of large fluid depths.

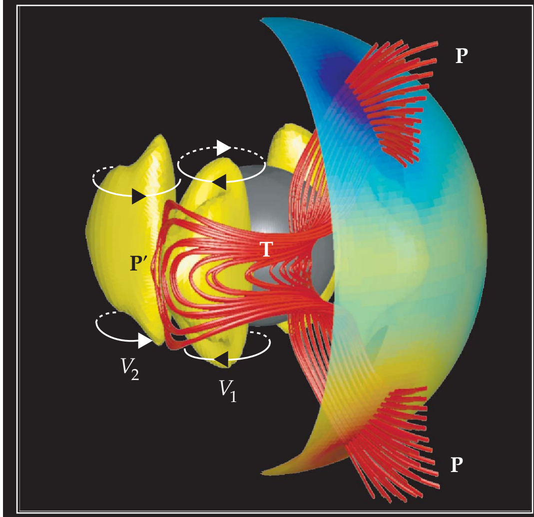
Theory, laboratory experiments, and numerical simulations show that the critical *Rm* for dynamo action is about 40. The *Rm* of the geodynamo can be estimated by measuring the electrical conductivity of core alloys at high pressure and high temperature and by inferring the fluid velocity from spacecraft measurements that track the motion of geomagnetic field lines emanating from the core. Because magnetic field lines move with the fluid where *Rm* is high, tracking the variation of the geomagnetic field traces the fluid motion in the outer core. That approach yields *Rm* between 1000 and 2000, well above the critical value.[9] The relatively fast flow speeds of nearly 1 mm/s in Earth's outer core may be far greater than in other terrestrial planets because their mantles, lacking plate tectonics, are less efficient at heat transport. Indeed, the simplest explanation for why some planetary dynamos failed quickly is that heat transport in their mantles became too low to maintain supercritical *Rm* conditions in the core.

Magnetic induction by flow

The box on the left illustrates the basic form of convection and dynamo action in Earth's outer core as they are currently envisioned. Theory, laboratory experiments, numerical simulations, and geomagnetic observations are in fundamental agreement that convection in the outer core consists of vortices aligned in the direction of the rotation axis. The alignment is a consequence of the dominance of the Coriolis acceleration and is an expression of the so-called Taylor–Proudman constraint familiar in rotating fluid mechanics.

The geodynamo in action

The geodynamo converts the kinetic energy of fluid motion in Earth's core into magnetic energy. The motion of liquid iron couples to an initial, already existing magnetic field and drags the field lines in the direction of the flow via Faraday induction. (For a tutorial on how that works in a laboratory setting, see the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40.) This snapshot of the geodynamo in action illustrates the process in a planetary context.



The partially transparent outer spherical surface shown here represents the boundary between the electrically conducting, fluid outer core, where dynamo action is concentrated, and the solid mantle; the gray sphere represents the solid inner core. Earth's rotation and the buoyant convection of molten metal produce vortices, depicted in yellow, that circulate the flow in directions set by the Coriolis force. Geomagnetic field lines are shown in red; blue shading on the core–mantle boundary denotes a negative, inwardly directed field, and yellow–red shading denotes a positive, outwardly directed field.

A feedback loop acts to sustain the illustration's existing, south-pointing dipolar magnetic field **P**. As that field is sheared and twisted by the current in vortex V_1, two bundles, oriented east–west, of toroidal magnetic field **T** are induced, one on each side of the equator. Helical flow between vortices V_1 and V_2 then rotates and stretches the toroidal magnetic field bundles, which in turn induces a secondary south-pointing magnetic field **P′**. And that field tends to amplify the original dipolar field **P**. (Figure courtesy of Julien Aubert.)

Columnar convection is particularly efficient at dynamo action because of a kinematic property called helicity, which, simply put, corresponds to the flow of fluid parcels along helical paths. As described in the box, the helical flow of molten iron allows for the induction of a toroidal magnetic field from a poloidal magnetic field and vice versa. The helical flow thus provides the positive feedback between the two magnetic field components that is essential for dynamo action. The sign of helicity is also significant, being generally negative in the northern hemisphere of the core and positive in the southern hemisphere. The antisymmetry is the primary reason why the geomagnetic pole, when averaged over time, tends to coincide with Earth's rotation axis.

Flipping fields

In addition to sustaining Earth's magnetic field, the geodynamo's supercritical state is responsible for polarity reversals. As figure 2a illustrates, reversals have occurred throughout history, although with a highly variable frequency. The recent geomagnetic field has reversed rather frequently on average—about four times per million years—despite the fact that the current polarity epoch, the Brunhes chron, has persisted for about 780 000 years.

Figure 2 also shows that three times in the current era the geomagnetic field basically stopped reversing for tens of millions of years—periods known as geomagnetic superchrons. Further into the past the geomagnetic record becomes increasingly sketchy; even so, evidence suggests that the alternation between reversing and nonreversing behavior has characterized the geodynamo for a very long time.

Polarity reversals of the solar dynamo occur every 11 years, almost like clockwork. In contrast, reversals of the geodynamo are more widely spaced in time and occur far less regularly. The consensus view is that geomagnetic reversals have their origin in perturbations in the magnetic field of the core, rather than in external disturbances. But unlike the solar dynamo, reversals are not essential to the geodynamo process. Instead, frequent reversals indicate that the core is "overpowered" compared with its average state, and superchrons indicate that the core is "underpowered."

That interpretation is supported by systematic investigations of the polarity reversal process using first-principles numerical dynamo models,[10] which show that although the timing of individual reversals is basically random, physical factors influence their likelihood. For example, increasing the angular velocity of planetary rotation tends to stabilize dynamo magnetic fields against polarity reversal, whereas increasing the vigor of convection tends to have the opposite effect. An increase in large-scale shear flow also often tends to increase the likelihood of a reversal.

Figure 3 illustrates a reversal in a simulated dynamo through a series of snapshots, each separated by 4000 years. Initially, as shown in column a, the radial magnetic field intensity on the core–mantle boundary is strongly positive, as is the axial dipole moment of the field. The reversal process begins in a region of the core where convection happens to be

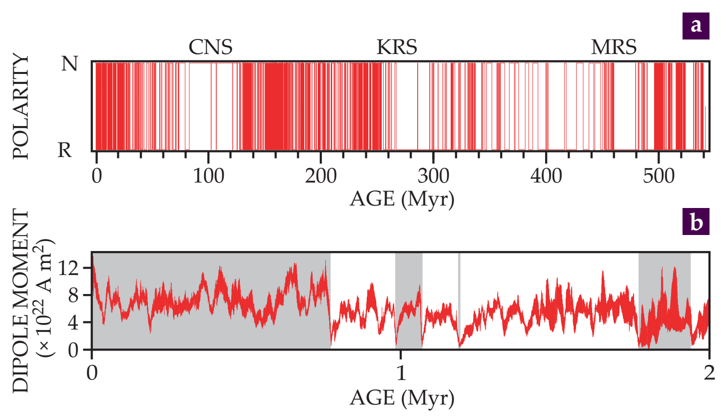


Figure 2. Geomagnetic polarity reversals in history. (a) Normal (present-day) and reverse polarity are denoted by N and R, respectively. Each line in the record signifies a transition, upward or downward, from one polarity to the other. So variations in the number of lines per unit length represent variations in the reversal frequency. The average frequency is nearly two reversals per million years, but three long periods of stable polarity—the superchrons labeled CNS, KRS, and MRS—also occurred. (Adapted from ref. 12.) **(b)** The axial component of the dipole moment can be obtained from magnetization of ocean-floor sediments, assuming the geomagnetic field at a given time in history is, in fact, an axial dipole. Shaded and white backgrounds correspond to periods of normal and reverse polarity, respectively. The dipole moment drops sharply around polarity reversals. Less dramatic drops correspond to magnetic excursions, often interpreted as failed reversals. (Adapted from ref. 13.)

particularly vigorous and magnetic field lines experience anomalously large amounts of twisting and bending by virtue of the high rates of strain in the fluid motion—enough bending to locally reverse the magnetic field direction. The blue-colored magnetic field lines in the middle row reveal one locally reversed region.

Because the fluid velocities are somewhat higher in that region, the local *Rm* may be higher as well compared with the rest of the core. And if conditions for growth are favorable, the reversed magnetic field there will intensify faster than in surrounding regions. Under those circumstances, the reversed field expands and occupies an increasingly larger portion of the core until the polarity of the magnetic field inside the core becomes mixed, as in columns c and d, and it leads to a sharp drop in the magnitude of the geomagnetic dipole moment, normally the dominant and most stable component of the external geomagnetic field.

What remains of the external field after dipole collapse is a low-intensity, spatially complex superposition of the weak dipole plus higher-harmonic components, the so-called transition field. What happens next depends on poorly understood details of the way the dipole field regenerates. It could regenerate with its old polarity, completing what's called a polarity excursion. Or it could emerge with the opposite polarity and complete the reversal.

Evidence of reversals

Geomagnetic reversals and excursions can usually be identified on the basis of rock magnetization

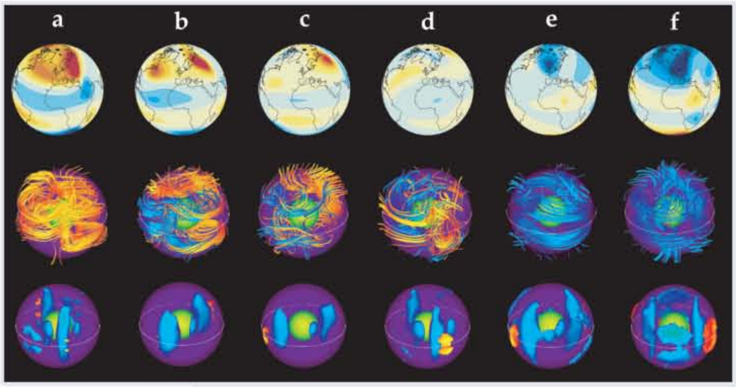


Figure 3. Polarity reversal in a numerical dynamo. These sequences of images, produced by solving the coupled Navier–Stokes and magnetic-induction equations in a rotating spherical shell,[10] illustrate the evolution of the magnetic field and convective flow inside Earth's core during a simulated geomagnetic reversal. Time progresses left to right, from columns **a** to **f** in approximately 4000-year steps. **(top)** In these contour maps of the radial component of the magnetic field intensity on the core–mantle boundary, red represents a positive field and blue a negative field. The initial, primarily dipolar pattern weakens in time and then flips orientation. **(middle)** Magnetic field lines also illustrate the progression. Red and orange field lines make a positive contribution to the axial dipole moment when passing the equator, and blue lines make a negative contribution. The purple sphere is the core–mantle boundary, and the green sphere is the solid inner core. **(bottom)** In these convective-flow snapshots, blue and red denote surfaces of clockwise and counter-clockwise flow, respectively. Elongated clockwise vortices twist the magnetic field lines into helical bundles and induce a coherent toroidal field and a strongly dipolar field. Curiously, the structure of the flow in the westward-drifting vortices changes little during a reversal.

alone, because to a good approximation, the directions of the magnetization before and after the reversal correspond to the directions produced by an axial dipole. In contrast, variations in geomagnetic intensity are far more difficult to extract from the rock record.

Nevertheless, geomagnetic intensity variations obtained from the magnetization of deep ocean sediments provide dramatic evidence of the reversal process. Figure 2b offers a two-million-year reconstruction of the variations of the geomagnetic dipole moment derived from magnetized ocean sediments worldwide. The quantity shown is called the virtual axial dipole moment, because the field model used to interpret the sediment magnetization consists of just an axial dipole. The figure shows that the dipole intensity drops by a factor of five or more over several thousand years prior to reversal and then recovers on approximately the same time scale, if not slightly faster. It also shows that for every successful reversal, there are several excursion events in which the dipole moment dropped substantially but has returned to its old polarity.

The behavior of the modern geomagnetic field offers clues to how the reversal process may begin. Ever since the first measurements by Carl Friedrich Gauss early in the 19th century, the geomagnetic dipole moment has been in steep decline, losing intensity at a rate of nearly 6% per century. That's about 20 times as fast as free decay, the rate at which the field would decrease by ohmic resistance were the dynamo to shut off. Indeed, it is sometimes said that we live in an "antidynamo" era. However, the evidence suggests that magnetic energy in the dipole field is actually being transferred—cascading up the geomagnetic spectrum to higher-multipole field components, precisely the action that causes dipole collapse in numerical dynamos.

Figure 4a shows a map of the modern geomagnetic field at the core–mantle boundary, the top of the active dynamo region. It was made from satellite magnetic field measurements extrapolated down to the core boundary on the assumption that the mantle is an insulator. The map reveals that the axial dipole, which dominates the geomagnetic field outside the core, emanates from a handful of high-intensity patches, two of which appear aligned roughly along longitudes 90° E and 110° W and are suggestive of the columnar symmetry expected for convection in the outer core. There is much nondipole structure in figure 4a—particularly in regions where the field has reversed polarity. Such locally reversed regions now cover a substantial fraction of the core–mantle boundary, and their sudden development over the past few hundred years largely accounts for the observed rapid decrease in the geomagnetic dipole moment.

For interpreting the geodynamo, it is important to distinguish transient structures in the modern geomagnetic field

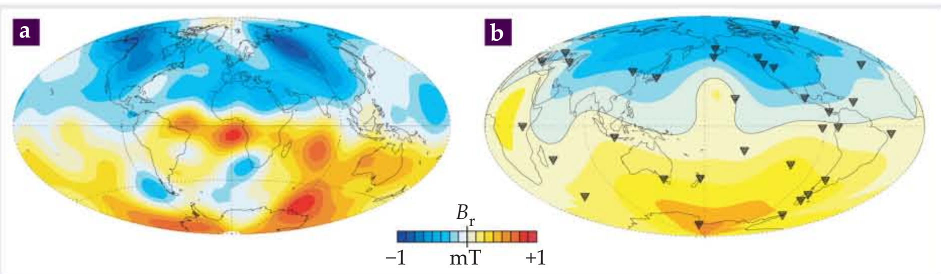


Figure 4. Maps of the radial component of Earth's magnetic field B, as projected onto Earth's core–mantle boundary, with continent outlines drawn for reference. **(a)** This modern geomagnetic field map, based on measurements by the *CHAMP* and *Oersted* satellites, illustrates the dipole as composed of transient patches of field. **(b)** This geomagnetic field map, averaged over the past 5 million years, is derived from normal-polarity paleomagnetic directions and intensities measured in volcanic rocks from some 1400 worldwide sites, binned into 34 regions (triangles). (Updated from ref. 14, courtesy of Catherine L. Johnson.)

from those that are long lasting. Figure 4b shows a map of the geomagnetic field derived from paleomagnetic measurements averaged over the past 5 million years. The axial dipole field is even more dominant in that map than in the modern snapshot. Yet significant nonaxial structure persists, especially in the northern hemisphere, where the two high-intensity flux patches are smeared out into high lobes separated by a relatively weak field beneath the Pacific Ocean and Africa.

The significance of the nonaxial structure becomes apparent when its 5-million-year persistence is measured against the characteristic time scales of motions in the core and mantle, which are centuries and tens to hundreds of millions of years, respectively. The persistent deviations from axial symmetry in figure 4b are therefore far more likely due to the imprint of the mantle rather than being intrinsic to the geodynamo process.

Pushing the frontier

Recent progress on understanding the geodynamo does not mean that challenges have gone away; new vistas are opening as fast as old problems are solved. For example, fresh evidence exists for a higher than expected conductivity in core materials,[11] which would further tax the already strained energy budgets of planetary dynamos. And in his companion article, Buffett explains that the inner core has acquired a three-dimensional structure that may record past events in geodynamo history.

Researchers need to make numerical dynamos more realistic and to accurately couple the dynamo process to mantle dynamics. Laboratory dynamos in spherical geometry may be just over the horizon (see the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40). And exoplanet discoveries promise a vastly expanded inventory of planetary dynamos if their distant magnetic fields can somehow be detected. Indeed, it appears that the most exciting part of the quest has just begun.

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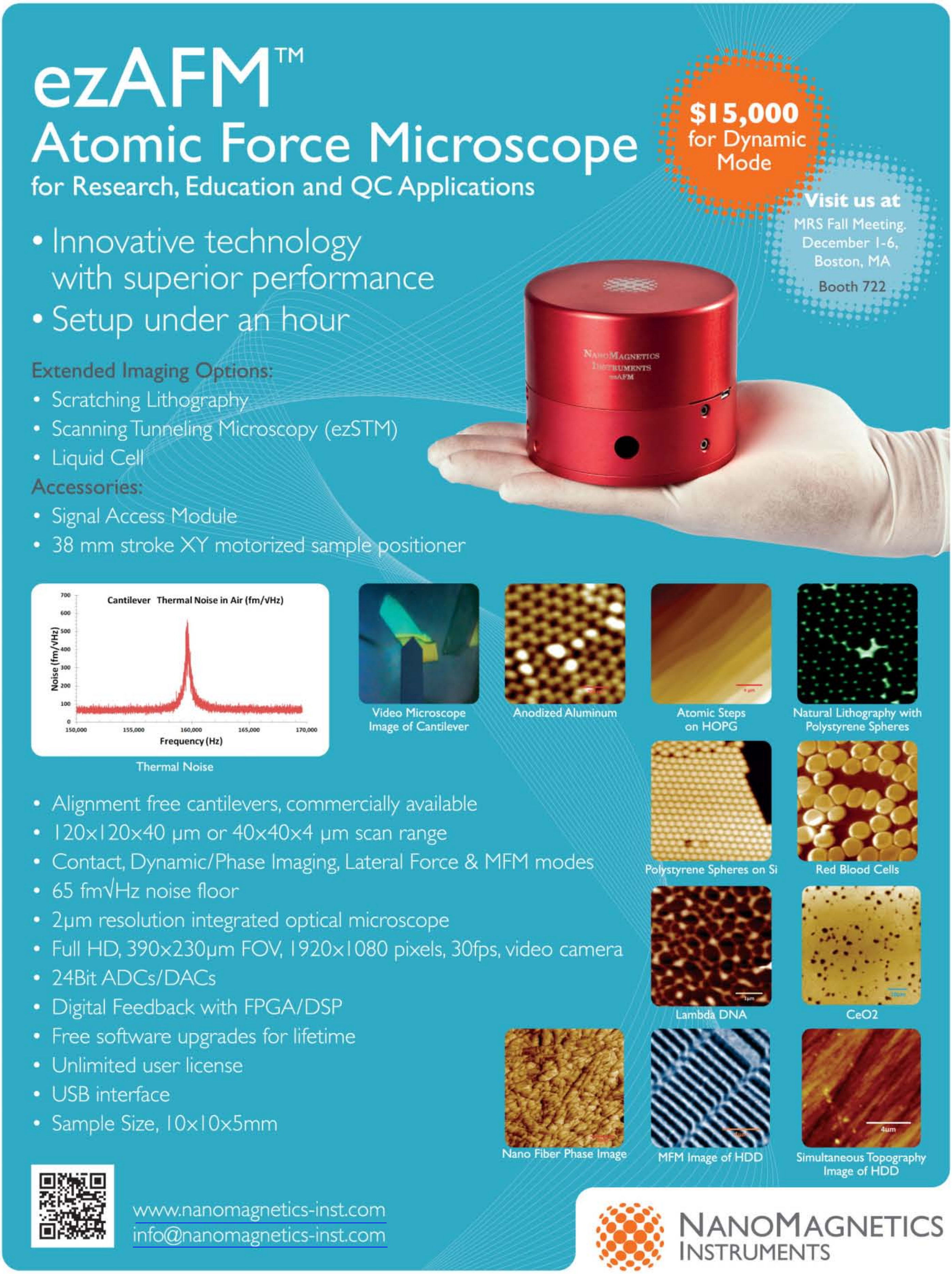
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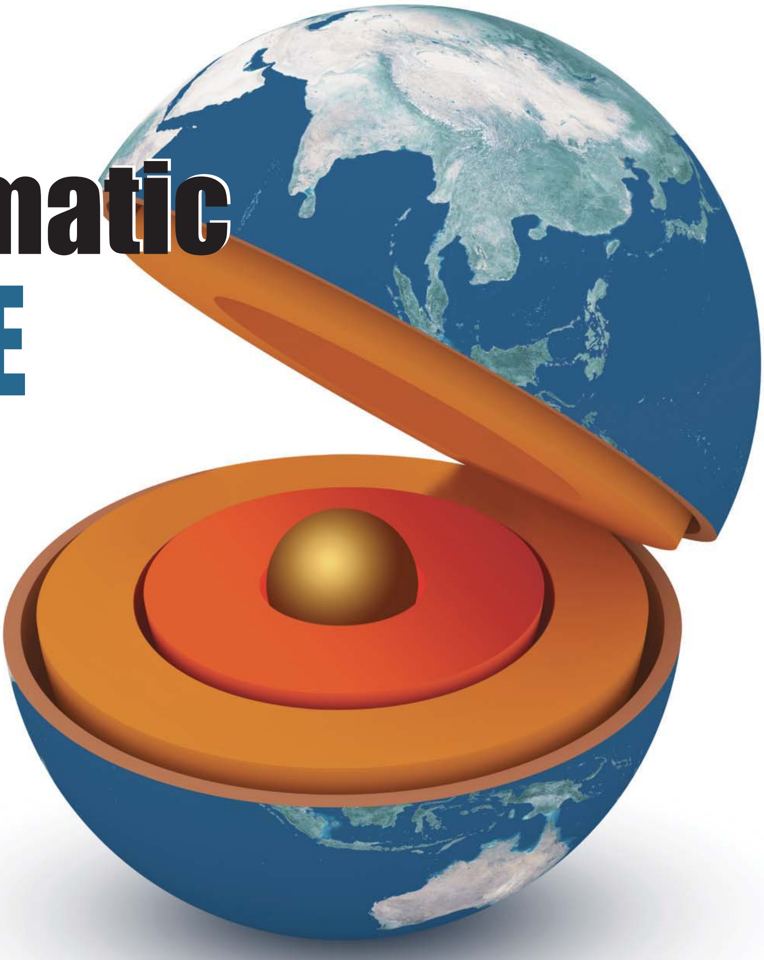
Earth's enigmatic INNER CORE

Bruce Buffett



The solid iron ball at the center of our planet helps power Earth's magnetic field and may record a billion years of geological activity in the deep interior.

If we could travel to the center of Earth, we would leave behind the rocky outer shell and enter the liquid iron core about halfway down. After we traversed 80% of the distance to the center, the liquid iron core would transform into a solid due to the crushing influence of pressure, even though the temperature is comparable to the surface temperature of the Sun. Crossing into the solid region brings us to Earth's inner core. Figure 1 illustrates the principal subshells that make up the planet.

Despite its small size–less than 1% of Earth's volume, with a radius the width of Texas–the inner core has a surprisingly large role in the dynamics of our planet's interior. Earth's gradual cooling causes the inner core to grow at roughly 1 mm/yr by solidification of the liquid surrounding it. The release of latent heat and the exclusion of impurities in the liquid iron produce buoyant fluid that stirs the outer core and generates Earth's magnetic field. Indeed, more than half of the power currently needed to generate the magnetic field is probably derived from inner-core growth.[1]

Propagating seismic waves through Earth illuminates the planet's internal structure much as x rays illuminate features of the body in medical imaging: Differences in physical properties alter the waves' absorption, scattering, and transmission, which permits the structure to be reconstructed from surface observations. A growing collection of observations reveals unexpected complexity in the inner core. Evidence for lateral variations in seismic-wave speed and attenuation is inconsistent with simple expectations of slow radial growth from a well-mixed liquid. More enigmatic is the evidence for elastic anisotropy, which causes seismic waves to travel several percent faster along polar paths than equatorial paths.

There is no consensus on the origin of elastic anisotropy or most of the other structure, but researchers suspect that the complexity is a record of past dynamics. Understanding how to read that record offers an opportunity to gain new insights into the history of our planet; it may also reveal the reasons why Earth evolved so differently from its nearest planetary neighbors.

Discovery and surprises

In 1936 seismologist Inge Lehmann proposed the existence of an inner core, based on the reflection of seismic waves from its surface.[2] Proof that the inner core is actually solid would have to wait 35 years until measurements of Earth's elastic normal modes confirmed the need for finite rigidity at the planet's center.[3] That observation supported the prevailing view that the inner core forms by solidification and grows outward as Earth cools. Thermal modeling suggests that the inner core's diameter has grown by 8 cm since the time of its discovery—far too small a change to detect in seismic-wave observations.

Most modern studies rely on differential travel-time measurements, which compare the propagation times of waves that pass through and just above the inner core. Careful selection of earthquake and receiver locations establishes propagation paths that are nearly coincident through much of Earth's interior, so anomalies in the differential travel time can be attributed mostly to propagation through the inner core, as outlined in figure 2. In the mid 1980s evidence for the elastic anisotropy in the inner core

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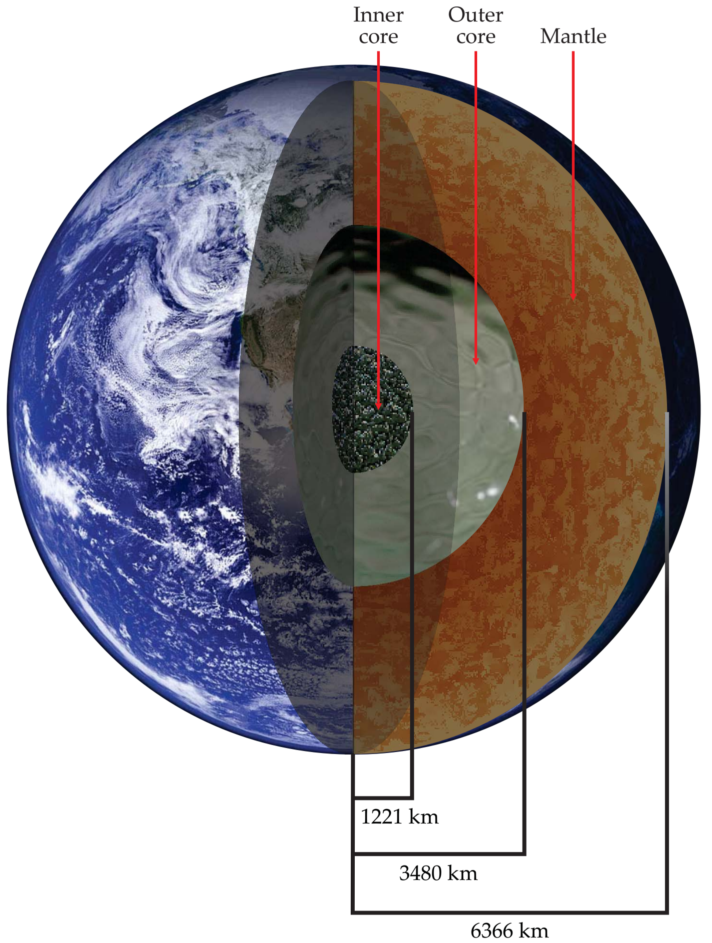


Figure 1. A cross section of Earth's interior reveals a rocky outer shell (mantle) and a metallic core. The core is made up mostly of iron, although impurities lower the density below that of pure iron. The gradual solidification of the liquid outer core produces a solid inner core. The density of the inner core is more consistent with pure iron, which implies a lower concentration of impurities than are in the surrounding liquid. (Figure courtesy of Eric King.)

began to appear;[4] independent support for it also came from observations of seismic normal modes, which represent elastic vibrations of the entire planet.

The unexpected discovery of elastic anisotropy initiated a flurry of activity. As subsequent studies provided more thorough coverage of the inner core, the complexity required to explain the observations steadily increased. Several consistent features emerged, including hemispherical differences in the strength of anisotropy:[5] Strong anisotropy is required in the western hemisphere to account for large travel-time anomalies, whereas weak anisotropy is sufficient to explain the behavior of waves that pass through the eastern hemisphere. There is little evidence for anisotropy in the top 100 km of the inner core, but support is growing for a distinctly oriented anisotropy at the inner core's very center. Limited observations suggest that the slow direction is tilted by 45° from the equatorial plane.[6]

Another surprise was the discovery in the mid 1990s of anisotropy in the attenuation of seismic waves.[7] Higher attenuation of the waves' intensity in the inner core is often associated with faster propagation speeds. That behavior is opposite to the usual dispersive effects in imperfect elastic solids. Scattering of seismic waves is a likely explanation, possibly due to regions of distinctly oriented iron crystals in the inner core. Explaining the large-scale anisotropy in attenuation requires scatterers that are both aspherical and preferentially aligned.

Interestingly, a strong correlation between wave speed and attenuation is also found in regions, such as the upper 100 km, that lack strong elastic anisotropy. For example, wave speeds in the upper 100 km appear to be nearly isotropic, yet geographic areas with high attenuation tend to correspond to higher-than-average wave speeds. One suggestion is that variations in the size of iron crystals in the top 100 km of the inner core could account for both the attenuation and velocity.[8] Crystal sizes ranging from tens of meters to tens of kilometers may be enough to explain the observations, but those crystals would need to be randomly oriented in the upper 100 km of the inner core to ensure that the velocity in that particular region remains nearly isotropic.

Thermal models

Growth of the inner core cannot be detected in observations, but it can be predicted using models for the thermal evolution of the core. Cooling is driven by heat conduction into the base of the rocky shell that surrounds the core. That shell, known as the mantle, is more massive than the core and has a high effective viscosity, which accommodates slow thermal convection with velocities on the order of 0.1 m/yr. Comparatively rapid flows on the order of 10^4 m/yr can be driven in the low-viscosity liquid core by temperature anomalies of only a few millikelvin.[9] Ultimately, convection in the mantle regulates the cooling of the core and sets the pace of inner-core growth.

Temperatures in the core were probably high enough in the distant past to ensure that the entire core was liquid. Gradual cooling eventually caused the temperature at Earth's center to drop low enough to nucleate an inner core. Solidification begins at the center because of the pressure dependence of iron's melting curve, shown in the box on page 40. The intersection of a steep melting curve with the temperature of the core–often approximated by assuming a well-mixed fluid with constant entropy–defines the radius of the inner core. The current size of the inner core reflects the total amount of heat that has been removed from the core as a whole since the inner core began to grow. Over that time, the top of the core has cooled by about 60 K.

The rate of inner-core growth is set by the average heat flux into the base of the mantle. Cooling drives solidification, but the release of latent heat reduces the resulting change in temperature. In addition, impurities in the liquid-iron core are excluded from the solidifying inner core, judging from seismic estimates of the density change across the inner-core boundary. Those impurities produce buoyant fluid that helps to stir the liquid core. The result is

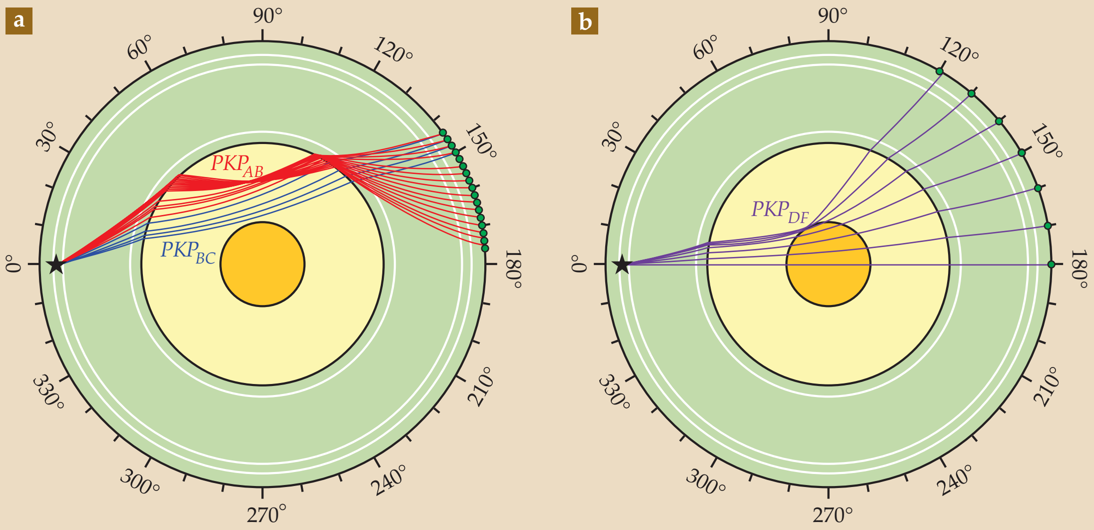


Figure 2. Seismic waves illuminate Earth's internal structure. Compressional waves that travel from one location (designated by the star)—typically an earthquake—through the mantle (green) and core to another location on the surface are often denoted *PKP*. Different paths through the core are possible. **(a)** The sets of paths *AB* (red) and *BC* (blue), which differ in the extent of refraction they experience at the core–mantle boundary, travel entirely through the liquid core (pale yellow). **(b)** Paths *DF* (purple), in contrast, travel through the inner core (orange) as well. Differences in the travel time between the *BC* and *DF* paths are primarily due to propagation through the inner core and thus can be used to discern aspects of its structure. (Figure courtesy of Ed Garnero.)

a segregation of impurities into the liquid core and a decrease in Earth's gravitational potential energy. Nearly all of that energy ends up in the core as heat, which also buffers the change in temperature. The inner core's evolving composition can further slow the rate of solidification for a prescribed heat flux.

Models for inner-core growth are hampered by substantial uncertainties in many of the relevant physical properties, but most recent models suggest that the inner core grew to its current size in 1 billion years or less.[1] Before that time, convection in the core would have been driven primarily by cold, dense fluid sinking from the core–mantle boundary as the core cooled. Peter Olson describes the dynamics of convection and magnetic field generation in the companion article on page 30.

Dynamics

Geological observations of magnetization in ancient rocks demonstrate that Earth has possessed a magnetic field for at least the past 3.2 billion years.[10] The persistence of the magnetic field implies that the liquid core has been convectively stirred for most of Earth's history. Once an inner core formed, its growth introduced new physical processes; a record of those processes is imprinted on the growing sphere.

Thanks to the low viscosity of liquid iron, the solid inner core can rotate relative to the mantle. Early numerical models of convection and field generation[9] in the liquid core predicted inner-core rotation rates of roughly one degree per year. In those models, eastward flow at the base of the liquid core carried the inner core in the same direction on average.

A subsequent search for the rotation by seismologists revealed an intriguing change in travel time for waves that propagate through the inner core.[11] Waves that travel from nearby earthquake locations to fixed receivers on the surface pass through different parts of the inner core if it rotates with time. Initial estimates for the change in travel time were interpreted as eastward rotation of the inner core, although several subsequent studies have challenged the existence of any rotation;[7] inner-core rotation is plausible on physical grounds, but its detection in seismic observations remains controversial.

Another type of motion is caused by the thermal convection inside the inner core. In the absence of substantial heat sources, convection is expected when rapid growth of the inner core leaves little time for conductive cooling. In that case, warm, buoyant material develops below colder, dense material. Such a density stratification is unstable to convective overturn by creeping flow, even though the inner core is solid. By contrast, slow growth of the inner core allows time for conductive cooling, which in turn allows material at the center of the inner core to become cold and dense. And in that scenario, the density stratification is stable and convection will not occur. Current estimates suggest that the inner core lies close to the transition between stable and unstable stratification. Changing the value of thermal conductivity within the present uncertainties is enough to switch between convecting and nonconvecting states.

Even if the inner core was convectively unstable at early times, a number of factors can subsequently suppress convection. Latent heat release and chemical segregation become more important in the heat budget of the core as the inner core grows in size. As a result, the rate of growth inevitably decreases with time and may eventually tilt the balance in favor of a stable thermal stratification. In addition, an increasing concentration of impurities in the liquid core can drive slightly higher levels of impurities into the solid during subsequent growth. A stable, chemical stratification can develop with time, particularly when the inner core becomes large, although the details depend on how impurities partition between the liquid and solid phases at high pressures and temperatures. There is plenty of uncertainty—even the identity of the impurities is not firmly established.

A surprising form of thermal convection is permitted by the presence of a phase transition at the inner-core boundary.[12] The usual form of convection—with a closed circulation of rising and sinking motion—is replaced by a nearly rigid-body translation. Melting in one hemisphere and solidification in the other closes the convective circulation. Two conditions are required for translational convection to occur. First, the inner core must be convectively unstable; second, its viscosity must be high enough to ensure that its shape changes primarily by melting and solidification rather than by viscous flow.

Rigid-body translation is strongly coupled to convection in the liquid core because melting and solidification depend on heat and the transport of material above the surface of the inner core. Simple parameterizations of turbulent transport have been used so far to describe the response of the liquid core,[12] but complications can arise from a combination of geometry, rapid planetary rotation, and the presence of a magnetic field. Surprises are waiting to be discovered as better models for coupled convection are developed.

The preceding discussion should dispel any notion that the inner core is static; instead, it is swept around by convection in the liquid core and may undergo its own internal convection. Even if the inner core is not convectively unstable, it is still subject to many other forms of deformation. For example, electric currents can produce heterogeneous heating.[13] That heating is not sufficient to drive convective overturn, but it can produce lateral variations in temperature, which induce a creeping flow.

In addition, the inner core is expected to solidify preferentially in the equatorial region due to the nature of heat transport in the overlying liquid. If the viscous flow of material is the primary means of relaxing boundary topography, then a large-scale flow can develop in the interior.[14] Flow may also be driven by magnetic stresses on the inner core,[15] possibly connected with inner-core rotation. Given the multitude of physical processes that can cause deformation, it is reasonable to ask if any of those processes can also explain the observed seismic structure of the inner core.

Origin of inner-core structure

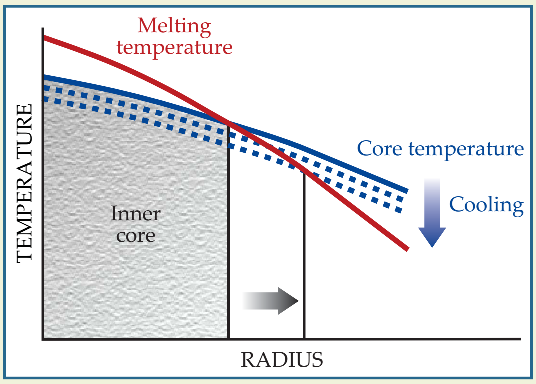
Elastic anisotropy in the inner core, illustrated in figure 3, is one of the earliest and most enduring mysteries to emerge from seismic observations. The presence of elastic anisotropy is usually attributed to preferential alignment of crystal lattices, although other structural features, such as oriented pockets of melt and large-scale chemical layering, can also give rise to anisotropy. A preferential crystal alignment, often referred to as texture, can be established at the time of solidification or may develop as a result of subsequent deformation.

Laboratory experiments suggest that the orientation of temperature gradients during solidification can establish an initial texture.[16] Numerical models of convection and magnetic-field generation have shown that temperature gradients at the inner-core boundary are primarily radial, although the magnitude of such gradients can vary with latitude. Expectations for crystals to align in the radial direction are consistent with the absence of strong anisotropy in the top 100 km of the inner core because a radial structure is invariant under rotation and should not produce faster wave speeds in polar directions.

Subsequent deformation of material with an initial solidification texture can produce the observed anisotropy, but that deformation must be influenced in some way by rotation because it is unlikely for fast paths to align with the direction of the rotation axis by chance. The required deformation could arise in a variety of ways. For example, thermal convection in the inner core can align with the

An outsized role for the inner core

Vigorous convection in Earth's liquid core continually regenerates the planet's magnetic field. An important source of buoyancy to drive the fluid motion comes from the growth of the inner core. Convective mixing homogenizes both the composition and entropy of the fluid, so the core temperature, plotted here (blue) as a function of radius, is well approximated by the condition of constant entropy. By comparison, the melting temperature of iron (red) is expected to have a stronger dependence on pressure. The intersection of the core-temperature and melting-temperature curves defines the radius of the inner core, which is currently 1221 km–about 20% of Earth's radius. At that depth, the melting temperature is estimated to be about 5500 K. As the core cools, the intersection point shifts toward larger radius and the inner core grows by solidification.



rotation axis, but only when the vigor of convection is relatively weak. Alternatively, preferential growth of the inner core at the equator can produce flow with a polar orientation as long as the viscosity of the inner core is not too high. It is also possible for electric currents and magnetic stresses to possess the correct symmetry because those features are associated with processes in the liquid core, which are strongly affected by the influence of rotation.

A second and more serious challenge is to explain the presence of hemispherical variations in elastic anisotropy. Electric currents, magnetic stresses, and local heat flow should all be heterogeneous over the surface of the inner core, but it is less obvious why the heterogeneity would be spatially persistent for long enough to establish a prominent deformation texture. A representative large-scale flow of several centimeters per year would produce strain rates on the order of 10^{-15} s^{-1} and would require about 10^7 years to accumulate enough strain to have observable consequences. If the inner core is free to rotate, one might expect significant averaging of structure in longitude, which would tend to erase hemispherical differences. Alternatively, the inner core may be locked in place by gravitational forces associated with mass anomalies in the mantle, although viscous deformation (or melting and solidification) can permit the inner core to escape the grasp of gravity.[17]

Translational convection is often suggested as a possible explanation for hemispherical differences,[12] particularly the hemispherical variations in isotropic velocity in the upper 100 km of the inner core.[7] However, extending the idea to explain the variations in anisotropy presents several unsolved challenges. First, translation causes little deformation, so any initial solidification texture at the surface of the inner core would simply be carried along by the nearly rigid-body motion. It is not clear how a strong anisotropy would develop in one hemisphere and disappear in the other without any additional deformation. Second, translation cannot explain the distinctly oriented anisotropy in the central part of the inner core (red region in figure 3). There is currently no simple explanation that accounts for all of the complexity of the seismic observations.

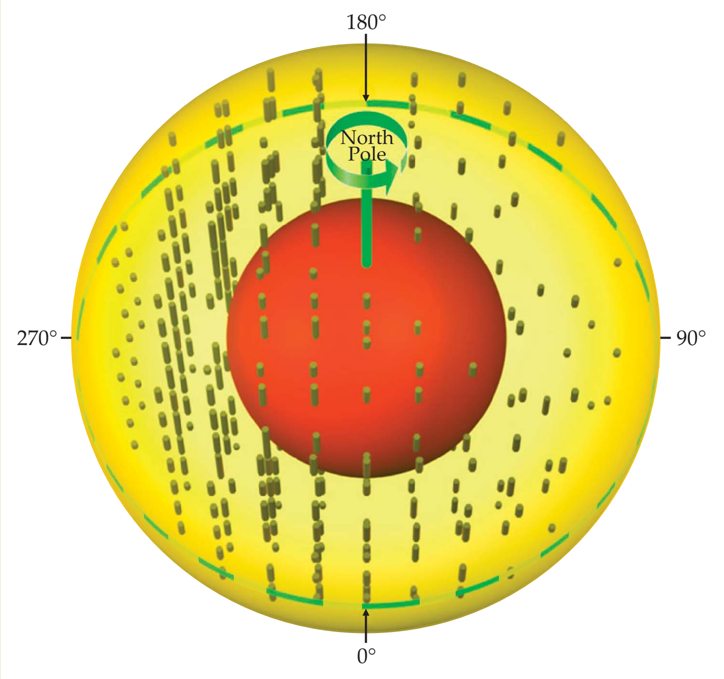


Figure 3. Elastic anisotropy in the inner core causes compressional seismic waves to travel fastest in the polar direction. The magnitude of the anisotropy, designated by the length of brown rods in that direction, varies across the inner core. Anisotropy is strongest in the western hemisphere (longitude 270°) and is much weaker in the eastern hemisphere (longitude 90°); the green dashed line represents the equator. The innermost region (red) of the inner core is also anisotropic, but with an orientation (not shown) thought to be tilted with respect to the poles. (Figure courtesy of Xiaodong Song.)

Gaining perspective

The seismic observations are, in a word, confounding. Simple expectations for slow growth of the inner core from a well-mixed liquid are completely at odds with clear evidence for structural complexity. Proposals abound to explain one aspect or another, but none currently provide comprehensive understanding. The attention given to the inner core may be surprising to some, given its small size, but there are few records of past dynamics in Earth's core. Fluctuations and reversals in Earth's magnetic field are recorded in rocks at the surface (see the article by David Dunlop, PHYSICS TODAY, June 2012, page 31), but the inference of internal dynamics is indirect because the magnetic dipole at the surface represents only a small fraction of the field inside the core. If the inner core is a battered relict of 1 billion years of evolution, then much can be learned from its seismic structure. In many ways the inner core is analogous to a rock outcrop for a geologist. Long and elaborate tales have been told from a small patch of rock, and the same may be true for the solid iron ball at Earth's center.

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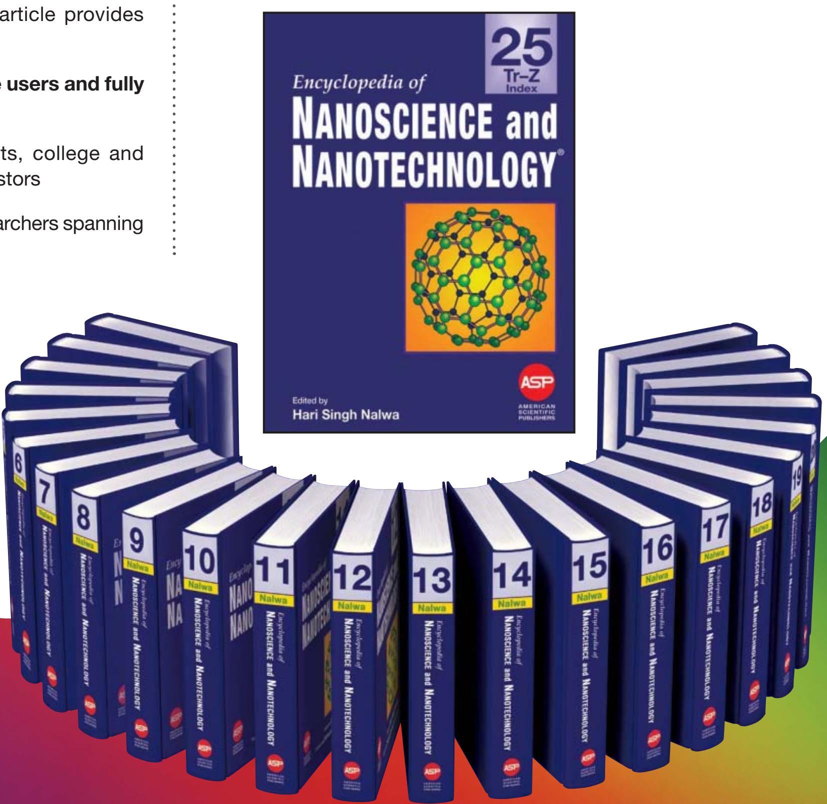

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The Arecibo Observatory: Fifty astronomical years

Daniel R. Altschuler
and Christopher J. Salter

A giant eye embedded in the karst region of northern Puerto Rico, the Arecibo radio telescope looks into the universe. (Courtesy of the Arecibo Observatory.)

Among its many accomplishments, the world's largest single-dish telescope has detailed properties of the ionosphere, spotted the first planets discovered outside our solar system, and helped confirm the general theory of relativity.

Running along the north coast of Puerto Rico, a modern expressway links the bustling capital of San Juan with the town of Arecibo to the west. As you turn south from Arecibo and head into the interior of the island, the roads become progressively narrower and the curves sharper. The route ascends the rugged karst terrain, and images of the modern metropolis rapidly fade into rustic scenes in which dogs and chickens roam freely and ferns, grasses, wild orchids, and the broad shiny leaves of banana plants cover the slopes. This is the Puerto Rico of the past, now rapidly changing.

A few kilometers beyond the small town of Esperanza, you arrive at the gate of a different kind of island—the Arecibo Observatory, an NSF facility operated for its first 48 years by Cornell University and since 1 October 2011 by the research institute SRI International, the Universities Space Research Association, and Universidad Metropolitana, a private university in San Juan.

Suddenly, the rural scenery gives way to an ultramodern technological landscape. For half a century, Arecibo's giant metal eye has operated at the cutting edge of research, gathering feeble radio waves as they arrive from the cosmos, enabling radar experiments on both solar-system bodies and our planet's ionosphere, and contributing a wealth of information to humankind's astronomical and geophysical knowledge base.

Evolution of a giant

The Arecibo Observatory, incorporated since 1971 into the National Astronomy and Ionosphere Center, grew from an idea of William E. Gordon (shown in figure 1), then a professor of electrical engineering at Cornell University. Gordon's research interest was the ionosphere, the highly rarefied region of Earth's atmosphere above about 80 km. At that altitude, high-energy UV and x-ray photons arriving from the Sun interact with the atmospheric gases and create a plasma of positively charged ions and negatively charged electrons. When a powerful radio wave is transmitted toward the ionosphere, a very small fraction gets scattered back by the electrons. Studying the returned radiation with a technique called incoherent scatter radar (ISR) can provide details of the density and temperature of ionospheric electrons, ionic composition, ionospheric winds, and more.

Daniel Altschuler was director of the Arecibo Observatory from 1991 to 2003 and is now a professor of physics at the University of Puerto Rico, Río Piedras. **Chris Salter** is a senior research associate at the Arecibo Observatory in Arecibo, Puerto Rico.

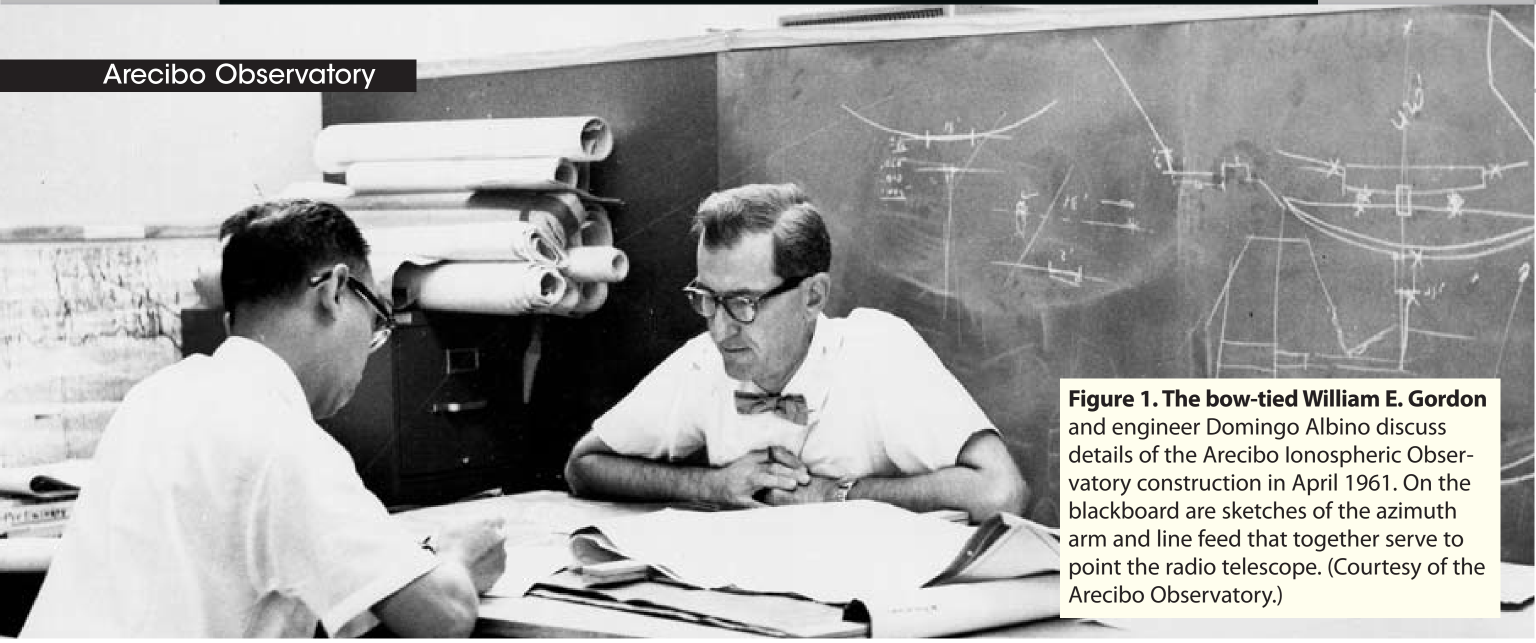


Figure 1. The bow-tied William E. Gordon and engineer Domingo Albino discuss details of the Arecibo Ionospheric Observatory construction in April 1961. On the blackboard are sketches of the azimuth arm and line feed that together serve to point the radio telescope. (Courtesy of the Arecibo Observatory.)

By Gordon's calculations, useful ISR measurements required an antenna with a diameter of about 1000 feet (305 m). To construct it, he and collaborators decided to use a spherical reflector, fixed to the ground but with a movable transmitter–receiver suspended above it.

In the summer of 1960, men and machines funded by the US Department of Defense moved into a sinkhole in the northern karst region of Puerto Rico and began transforming Gordon's vision into reality. Three years and $9 million later, the Arecibo Ionospheric Observatory was in operation under Gordon's personal direction; it formally opened on 1 November 1963. As planned, the antenna proved capable not only of investigating Earth's ionosphere but also of studying our solar system via radar techniques and researching objects at the farthest reaches of the universe. However, even those who planned and built the telescope could not have foreseen its career of scientific stardom. Indeed, 50 years and two major upgrades later, their brainchild is still Earth's largest single-dish telescope. In 2011 the instrument was christened the William E. Gordon Telescope.

The secret of pointing

Fixed to the ground, the Arecibo reflector cannot move. By contrast, the next-largest radio dishes—the 105-m-diameter Robert C. Byrd Green Bank Telescope in West Virginia and the Effelsberg 100-m telescope in Germany—can move and point to any chosen celestial position.

So, how does Arecibo point? Its secret lies in its being a spherical reflector. Whereas a paraboloid brings all radiation arriving parallel to its principal axis to a point focus on that axis, a spherical reflector focuses along a radius of the sphere; figure 2a illustrates the situation. Originally, so-called line feeds were employed to collect the reflected radiation. Those line feeds, when moved to lie along different radii, enable the telescope to point because, as shown in figure 2b, only radiation from the direction in which the line feed is pointing will be received.

A line feed has hundreds of slots through which radiation enters—or exits, if the antenna is transmitting. Their placement, and the cross section of the feed along its length, must be precisely controlled if the waves arriving at different heights along the line feed are to arrive in phase at its output flange. Unfortunately, a line feed has an inherent limitation due to dispersion, the dependence of phase velocity on frequency. Because of dispersion, a line feed has a central design frequency at which it works best, and performance deteriorates as the signal frequency moves away from that central value. In other words, a line feed works well only over a limited bandwidth—typically 10–40 MHz for the Arecibo equipment. As a consequence, multifrequency observations require a number of different line feeds.

Upgrades

Two main characteristics explain why, 50 years on, the Arecibo telescope still ranks among the world's premier instruments. First, it is the world's largest collecting area and will remain so for some time yet. Whereas other telescopes may need to observe a given radio source for several hours to collect sufficient photons for analysis, Arecibo would need just a few minutes. Second, having undergone two major upgrades, today's telescope is very different from the one inaugurated in 1963.

By the late 1960s, astronomers wanted to operate at higher frequencies for both radio astronomy and planetary radar. Arecibo's original 430-MHz (70-cm) radar could study the Moon and the terrestrial planets, Mercury, Venus, and Mars. However, a so-called S-band radar operating at 2380 MHz (12.6 cm) with 0.5 MW power would not only provide much higher resolution on those targets, it would also enable investigations of bodies at the distances of Jupiter and Saturn.

However, if scientists were to use S-band frequencies, the Arecibo telescope would need a new transmitter and receiver, plus a new, more finely crafted reflector. In general, the surface of a reflector requires a precision of 1/20 of the shortest operating wavelength. To operate at 430 MHz, Arecibo's original reflector had to be a perfect sphere to within about 3 cm—quite a feat for a 300-m-diameter dish, but still feasible. To work efficiently at the 12-cm

S-band wavelength required a precision of better than 6 mm, a much greater challenge.

The new reflector has a surface accuracy of 3 mm. The old mesh was replaced by 38 778 shaped aluminum panels, each about 1 m × 2 m; the total weight of aluminum in the reflector is about 350 tons. Small holes in each panel allow 44% of impinging sunlight to pass through. That feature helps vegetation to grow beneath the dish, which controls soil erosion and ensures structural stability. The upgraded telescope was dedicated in November 1974. During the ceremonies, the new radar made a celebrated transmission toward the globular cluster M13: the three-minute Arecibo message encoding information about humankind and our solar system.

The second upgrade was completed in 1997; figure 3 shows the result. A so-called Gregorian dome containing two large subreflectors was suspended from the feed arm. The subreflectors correct the spherical aberration of the primary reflector, bringing radio waves to a point focus at which any of a suite of receivers can be positioned. The observatory's receivers now explore the frequency range from 300 MHz to 10 GHz and essentially cover the complete 1- to 10-GHz window. The new system is achromatic; that is, it eliminates the dispersion problem that necessitated multiple line feeds for observations over a range of frequencies. Nevertheless, a 430-MHz line feed suspended from a movable carriage house still serves for atmospheric radar work.

The 1997 upgrade incorporated several other changes. A 16-m-high stainless steel mesh screen now surrounds the 1-km perimeter of the reflector. The screen shields the receivers from thermal radiation coming from the ground when the antenna is pointing near the telescope's limiting angle of about 20° off the vertical. A new transmitter located within the dome doubled the previously available S-band radar power to 1 MW. Together with the other improvements, that power boost has, in some cases, enhanced radar sensitivity by better than a factor of 10.

A noteworthy upgrade in its own right, the Arecibo L-band Feed Array (ALFA), installed in 2004, provided another significant advance in telescope capability. Previously, telescope usage for surveys had been limited by the relatively small field of view available with traditional single-pixel observations. ALFA, which operates over the 1225- to 1525-MHz band containing the 21-cm hydrogen hyperfine line, is a cluster of seven cooled receivers. A fiber-optic transmission system and back-end signal processors complete a seven-pixel radio camera.

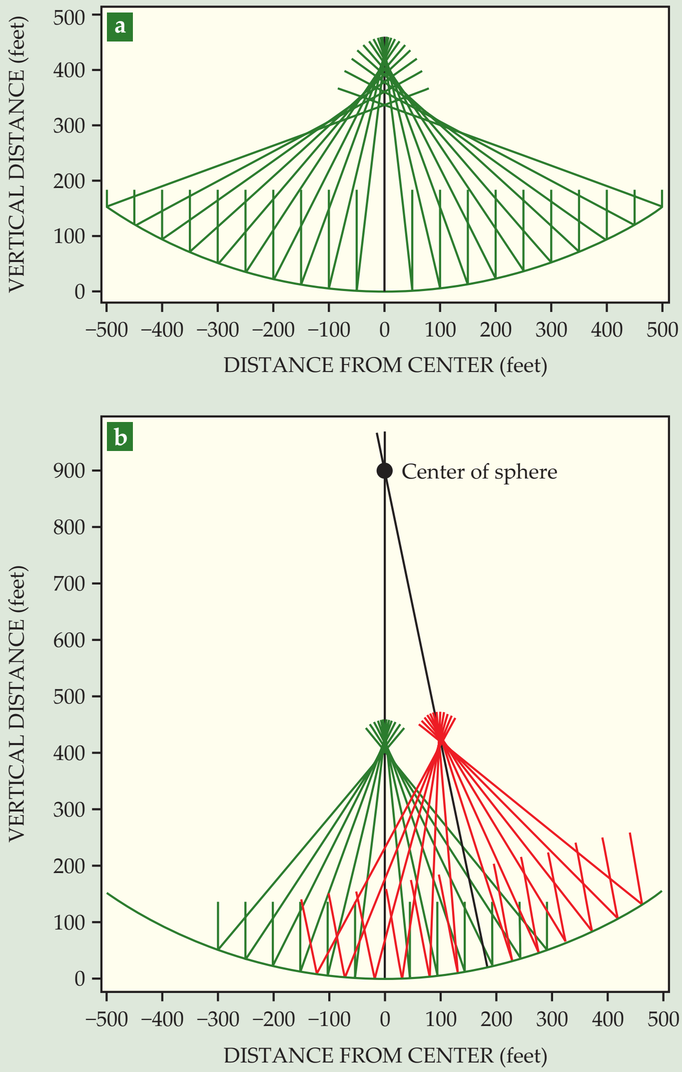


Figure 2. The geometry of spherical reflectors. (a) All incident parallel rays that strike the Arecibo dish a given distance from the center are reflected to a focus along a spherical radius. **(b)** Rays striking the dish from different directions are focused along different radii. Thus, by moving the line feed (the device that receives the reflected radiation), one can adjust the telescope so that it becomes sensitive to waves from different positions in the sky. But as the red rays show, when the telescope does not point vertically, it cannot take full advantage of its reflecting disk area.

From the Milky Way to deepest space

The 21-cm spectral line from the Milky Way's interstellar neutral hydrogen (HI) was first detected in 1951 at Harvard University's Lyman Laboratory by Edward Purcell and Harold Ewen. That radiation comes from hyperfine transitions in which the spin of a ground-state electron flips—before the transition, electron and proton spins are parallel; afterward, they are antiparallel. That hyperfine line is important because hydrogen is by far the most abundant element in the universe. Its intensity, line profile, and measured frequency provide information about the physical state of the emitting gas and, via the Doppler effect, its velocity along the line of sight. The first detection of HI outside the Milky Way occurred in 1953, when Frank Kerr and James Hindman detected it in the Magellanic Clouds. By 1960 a few tens of galaxies had had their HI signatures measured, but the study of HI in other galaxies was still in its infancy. The weakness of the detected signals necessitated the use of large antennas and sensitive receivers.

After Arecibo's 1974 upgrade, studies of the 21-cm HI line became an important area of the observatory's research. The early work involved detailed examination of individual galaxies and of the distribution of galaxies in space. Continuing

Figure 3. Arecibo today. In this view of the observatory, the reflector is surrounded by a mesh screen that shields the telescope receivers from radiation emitted by the ground. Pairs of cables attached to each corner of the suspended triangular platform control the height and orientation of the platform as the geodesic Gregorian dome moves. The dome's internal mirrors focus radio waves reflected off the main dish to a point. The visitor center is located at the base of the rightmost of the three 80-m-high towers. (Courtesy of the Arecibo Observatory.)

investigations of HI in galaxies have contributed hugely to our understanding of the large-scale structure of the universe, and Arecibo isn't done yet. In particular, three ALFA surveys are looking for galaxies—through their HI contents alone—at latitudes away from the plane of the Milky Way. Those three surveys complement each other. One covers a very wide area and is expected to detect more than 30 000 galaxies when fully analyzed. A second, deeper survey is studying specific galaxy environments—from specific isolated galaxies, through galaxy groups, to rich galaxy clusters. Deepest of all is a survey searching with unprecedented sensitivity for the HI in galaxies located within two tiny areas of sky.

Since the 1997 upgrade, which enabled observations up to 10 GHz, Arecibo has made several full 1- to 10-GHz spectral scans of luminous IR galaxies—objects that are forming stars at the highest known rate. Those scans have provided spectral censuses of molecules in the galaxies and have yielded a number of unexpected detections, including that of the prebiotic molecule methanimine, CH_2NH.

Pulsars

Perhaps Arecibo's most significant discovery to date, which earned Joseph Taylor Jr and Russell Hulse the 1993 Nobel Prize in Physics, was the 1974 discovery of the pulsar PSR B1913+16. Pulsars—rapidly rotating, highly magnetized neutron stars formed during the supernova explosions of massive stars—had been discovered seven years earlier by Jocelyn Bell and Antony Hewish at the University of Cambridge. As a pulsar rotates, opposing beams of radio emission originate from above its magnetic poles. If those beams sweep across Earth, they are detected as pulses. The Hulse–Taylor pulsar was the first one found to be part of a binary system, its companion being another neutron star. The orbital period of the system is only 7 hours and 45 minutes, roughly 1/1000 the yearlong orbital period of Earth about the Sun. Precise measurements of its pulses' arrival times, which continue at Arecibo to this day, confirmed the general theory of relativity's prediction of gravitational waves.

At the start of the 1990s upgrade, Alex Wolszczan undertook a pulsar search and found the first known extrasolar planetary system, PSR B1257+12, a pulsar orbited by three planets. By now, some 2000 pulsars have been identified, many of them discovered at Arecibo. ALFA is presently searching for new pulsars on the galactic plane and has made 123 new discoveries.

Some pulsars provide unique opportunities for testing theories of gravity and studying the properties of matter at extremely high densities. A fraction of pulsars belong to binary systems, in which orbital dynamics modulate the arrival times of pulses at Earth. The pulsar companions may be another neutron star, a white dwarf, or a main-sequence star. In one binary system, PSR J0737–3039, both components are radio pulsars; potentially, astronomers will discover other double-pulsar systems. The additional clock in those systems—that is, the second set of regular pulsations—permits novel tests of strong-field gravity. A radio pulsar with a black hole companion is perhaps the ultimate goal of pulsar searches; such a system would provide a unique laboratory for studying gravity in the strong-field regime.

Currently, the fastest spinning pulsar rotates 716 times per second. Next in line is PSR 1937+21, discovered by Arecibo in 1982, which spins 641 times per second. The discovery of pulsars that spin even more rapidly would help discriminate between the various equations of state proposed for neutron-star matter. Precise timing of millisecond pulsars is expected to reveal nanohertz-frequency gravitational waves. The North American Nanohertz Observatory for Gravitational Waves, or NANOGrav, has begun such an undertaking, with the Green Bank and Arecibo telescopes as its indispensable tools.

Synthesizing a vast telescope

Very long baseline interferometry (VLBI) is a variant of astronomical interferometry that uses simultaneous observations of an object made by an array of widely spaced telescopes. The various telescope signals are transferred to a central correlator after being recorded on disk packs or, in so-called eVLBI, after being passed directly over the internet. They are then combined to simulate a virtual telescope whose size equals the maximum separation between the telescopes involved. Thus VLBI achieves an impressive angular resolution, on the order of milliarcseconds or finer.

Given the faintness of many interesting radio sources, VLBI requires large collecting areas in its arrays. For example, the High Sensitivity Array includes the National Radio Astronomy Observatory's Very Long Baseline Array, the Green Bank Telescope, the Effelsberg 100-m telescope, and the Arecibo dish. Arecibo is also a member of the European VLBI Network and from 1997 to 2001 was involved in a new venture: space VLBI. During that time it was part of the terrestrial network supporting *HALCA*, the 8-m-diameter orbiting telescope operated by Japan's VLBI Space Observatory Programme.

As an example of Arecibo's contributions to VLBI (in this case, as part of the European VLBI Network), figure 4 presents a 5-GHz image of the famous jet in the Virgo-cluster galaxy M87. Arecibo provided the resolution needed to resolve the inner jet and the sensitivity needed to reveal the weak complex visible some 0.9 arcseconds from the core. Interestingly, the complex appears to move at superluminal velocities of 4–6.5 c. The apparent relativity-violating speeds are an optical illusion due to the motion of jets, ejected from the active galactic nucleus, that are traveling very near the speed of light at an angle close to the observer's line of sight.

Closer to home

At the public astronomy talks we've given, it seems that no matter the topic, someone in the audience eventually asks, Are we alone? or Have you detected *them* at Arecibo? Such musings are very old. More than 2000 years ago, Lucretius wrote in his *De rerum natura* (*On the Nature of Things*),

> I tell you
> Over and over—out beyond our world
> There are, elsewhere, other assemblages
> Of matter, making other worlds. Oh, ours
> Is not the only one in air's embrace.

The search for extraterrestrial intelligence (SETI) is an attempt to settle the issue. If, on another planet, a civilization has developed a communications technology that uses electromagnetic waves, we on Earth might be able to detect a message with a sufficiently sensitive telescope. Radio waves propagate unhindered through the interstellar dust that obscures starlight, so it seems appropriate to search in the RF waveband. Between April and July 1960, an 85-foot-diameter radio telescope in Green Bank, West Virginia, pointed at the stars τ Ceti and ε Eridani, some 11 light-years away. That was Project Ozma, the first search for signals from an alien technology, conducted by Frank Drake, who later became director of the Arecibo Observatory.

Until 2004, scientists of the SETI Institute took advantage of Arecibo's unsurpassed sensitivity to study a set of nearby solar-type stars in the hope of detecting an alien signal. Contrary to what many believe, no contact was made. Today several million people participate globally in the SETI@home program, in which recent Arecibo data are analyzed by home computers. The idea of a globally distributed computer network has been adopted for other large computing tasks such as molecular folding studies, climate simulations, and pulsar searches.

In our own solar system, radar had detected feeble echoes from the Moon as early as 1946. However, the planets remained elusive targets. In 1961 the NASA Jet Propulsion Laboratory's Goldstone radar obtained radio echoes from Venus. It used two 26-m antennas, one transmitting with 10-kW power—modest by today's standards—and the other receiving the echo. The Goldstone radar work paved the way for a greatly improved value of the astronomical unit, the average distance between Earth and the Sun—a quantity of critical importance to space exploration.

In April 1964, shortly after the Arecibo telescope's inauguration, Gordon Pettengill's team used it to determine that the rotation rate of Mercury was not the previously believed 88 days but instead only

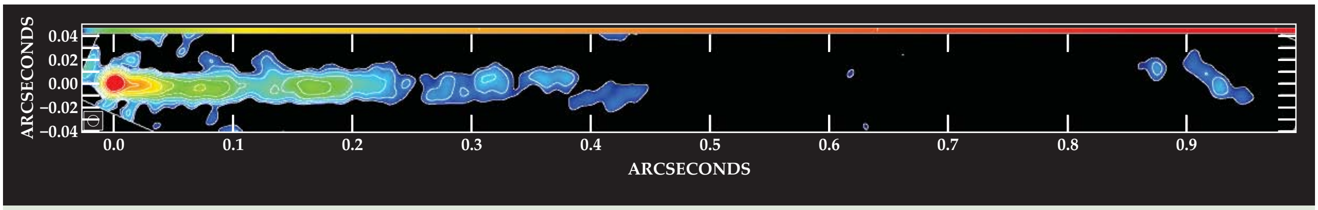


Figure 4. The inner region of the Virgo-cluster elliptical galaxy M87. Arecibo was an integral part of the European VLBI Network that generated the image. The nucleus of M87 lies at the far left; due to an optical illusion, the feature 0.9 arcseconds (260 light-years) to the right appears to move faster than the speed of light. Colors represent the intensity of emitted radiation—red regions are brightest; blue, faintest. (Courtesy of Marcello Giroletti.)

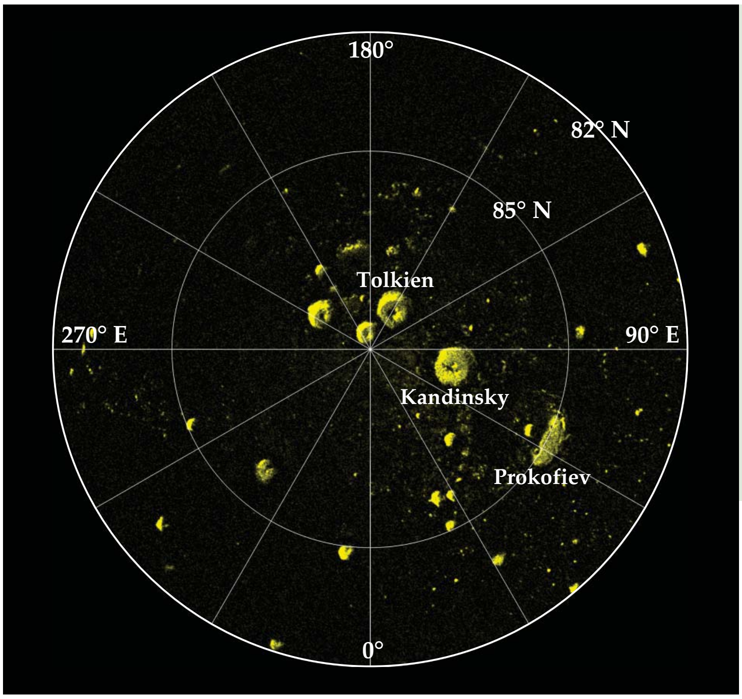


Figure 5. Deposits of volatile compounds lie on the shadowed floors of impact craters at the poles of Mercury. Because their radar scattering properties are similar to those of icy surfaces, the deposits are thought to be water ice. The discovery and imaging of such volatiles was a major contribution of the Arecibo Observatory to planetary astronomy. The figure shows the north polar region of Mercury with a resolution of 1.5 km. The donut shape of the deposits close to the pole is due to central peaks in the craters. Following the convention established by the International Astronomical Union for naming features on the innermost world, the names of craters on Mercury honor deceased writers, artists, and musicians. (Courtesy of John Harmon.)

59 days. Another surprising discovery concerning Mercury came in the late 1990s, when John Harmon found water-ice deposits at the bottoms of the planet's polar craters, where sunlight never reaches (see figure 5).

Over the years, the terrestrial planets, some moons of Jupiter and Saturn, Saturn's rings, and some comets have yielded their secrets to the Arecibo radar. So have a rapidly growing number of asteroids, especially the so-called near-Earth asteroids (NEAs) that come relatively close to our planet. To date, more than 300 NEAs, some as small as 50 m across, have been studied by the Arecibo radar with resolutions as fine as a few meters. The radar can obtain distances with a precision of 10 m and speeds accurate to 1 mm/s. The NEAs are of interest not only because of their potential to smash into us but also because the details of their structures hold clues to the origin and evolution of the solar system. About 15% of them are binary systems, consisting of two objects whose orbits about their center of mass allow accurate determination of their masses and densities. In 2008 Arecibo discovered a triple system, asteroid 2001 SN263. The Arecibo measurements yielded 75-m-resolution images of the 3-km-diameter asteroid, whose two moons are about 1.1 km and 400 m across. At the time, the triplet was 11 million kilometers away; imaging it with Arecibo's 75-m resolution was analogous to using a camera in New York to photograph a person in Los Angeles with 3-cm resolution.

Education and outreach

To the general public, Arecibo is best known from stories—false ones, to be sure—of how the observatory regularly communicates with "them," or from its extensive exposure in popular media. The observatory had a role in the major films *GoldenEye* and *Contact* and it placed first among the Learning Channel's "The Ultimate Ten Biggest Structures," where it beat out aircraft carriers, oil rigs, and the Hong Kong airport.

The 1997 inauguration of the Angel Ramos Foundation Visitor Center greatly enhanced the observatory's role in public outreach and education. Arecibo's visitor center is the only science museum serving Puerto Rico's population and its public and private schools, and it is setting an example for research centers nationwide. Pride in the observatory and an effective fundraising campaign inspired Puerto Rican organizations to contribute the funds needed for construction of the center. Particularly important was the contribution of the Angel Ramos Foundation, a philanthropic organization dedicated to improving educational, cultural, and civic conditions in Puerto Rico. NSF funded the exhibits.

Prior to 1997 about 25 000 visitors came to the observatory annually to view the telescope and listen to a rudimentary 10-minute audiotape. With the visitor center, that number has increased to about 100 000 per year; about one-third are students. Visitors encounter a modern facility with professionally prepared exhibits on physics, aeronomy, and astronomy, along with outdoor exhibits such as a solar-system model built to scale. An observation platform provides a unique view of the giant dish. Well over a million people have visited the center since its opening, and successful science-teacher workshops and high school research experiences have formed part of its educational activities.

A healthy future

Arecibo's 305-m eye has peered near and far for 50 years, contributing significantly to science. In parallel, its educational programs are contributing much to an interested public. Looking to the future, the observatory still has much to offer. This marvel of human inventiveness stands as a symbol of what humanity is, or should be, all about. Its three tall towers point skyward like the spires of a modern cathedral pointing to the heavens. It symbolizes a great human endeavor: our quest to understand the universe, which took off 400 years ago when Galileo Galilei first pointed his elementary optical telescope toward the sky.

The Arecibo telescope has had an important impact on large-telescope design. It is said that imitation is the sincerest form of flattery. The compliment was offered during 1975–85, when the 54-m-diameter spherical-reflector Radio-Optical Telescope was constructed in Armenia to enable work at millimeter wavelengths. Even today, the Arecibo model is serving as the basis for a new telescope, the Five Hundred Meter Aperture Spherical Telescope. Currently under construction in Guizhou Province, China, it should be completed in 2016. Its active surface will have a diameter of 500 m, with 300 m illuminated at any given time. It should operate at frequencies up to about 3 GHz and will have a slightly higher resolution than Arecibo for the most commonly used frequencies.

Arecibo itself continues to offer new and improved instrumentation to its user community. Within the past 12 months, it has upgraded its VLBI equipment to allow data recording at 2 Gbit/s. One exciting VLBI development has been Arecibo's collaboration with the Russian-led RadioAstron mission, whose 10-m antenna is in orbit. Recently, correlation of Arecibo data for the quasar B0235+164 with 5-GHz RadioAstron data taken 18 Earth diameters away produced a detection with a good signal-to-noise ratio and a resolution of about 55 microarcseconds.

The astronomical community can now take advantage of a new broadband pulsar recorder, PUPPI. For observers of both pulsars and HI, a next-generation L-band receiver array (AO40) is being developed to replace ALFA. Whereas ALFA observes 7 celestial positions simultaneously, the planned device will observe 40 and will open up remarkable possibilities for new surveys. A first cryogenically-cooled prototype with 19 reception elements was tested on the telescope this past July in a collaboration of Arecibo, Brigham Young University, and Cornell University.

Being astronomers, the two of us have concentrated almost totally on astronomical aspects of the Arecibo Observatory in this article. Sadly, we have hardly mentioned Arecibo's remarkable work in atmospheric and ionospheric physics during the past 50 years.[1] One aspect of that work has been ionospheric heating, in which the telescope transmits intense, low-frequency (less than 10 MHz) radio waves to the ionosphere, where they accelerate electrons. The resulting collisional heating generates plasma waves and other phenomena that can be studied with the 305-m dish via incoherent scatter radar. A new ionospheric heater is currently being installed on the main telescope and should commence operations soon.

A 2006 headline in the journal *Nature* declared that Arecibo might be "no longer dish of the day"; but then it never was! It has always been something of a gourmet dish, and definitely something very special.

Reference

1. For an excellent history of geophysical radar at the Arecibo Observatory, see J. D. Mathews, *Hist. Geo Space Sci.* **4**, 19 (2013). ■

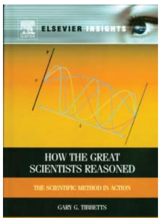
books

Method actors: Scientists and their practice

How the Great Scientists Reasoned
The Scientific Method in Action

Gary G. Tibbetts
Elsevier, 2013. $74.95 (176 pp.).
ISBN 978-0-12-398498-2

Reviewed by Peter Achinstein



Gary Tibbetts, in his lively and well-written book *How the Great Scientists Reasoned: The Scientific Method in Action*, declares that there is something called "the scientific method" (hence the subtitle) and that it can be stated very simply. Moreover, it is best understood not by reading books "on the theory of the scientific method" that Tibbetts finds "dry as dust and less gripping than a telephone directory," but by studying actual examples of great scientific discoveries, or at least great scientific moments.

Seven cases are considered: Christopher Columbus's discovery of the "Indies" (yes, that Columbus); the work of Antoine Lavoisier and Joseph Priestley on oxygen and the rejection of the phlogiston theory that attempted to explain combustion; Michael Faraday's contributions to electricity and magnetism; Wilhelm Röntgen's discovery of x rays; Max Planck on blackbody radiation and the introduction of the quantum; Albert Einstein's work on Brownian motion and atoms; and Niels Bohr's contributions to early quantum theory.

Tibbetts describes each of those discoveries or results in such a way that there is something for almost any reader. For a nonscientist craving biographical history, the book contains interesting and entertaining descriptions of the character, training, and motivations of the main players. For those seeking broad generalizations—the kind that philosophers of science love to make—there are indeed a few (very) broad ones. And for the technically minded, Tibbetts throws some mathematical formulas and concepts into the mix—not frighteningly complex ones, but enough of them to remind readers that the author is a working physicist who understands such things.

But can the book as a whole satisfy the needs of a broad range of readers? In examining how scientists reason, various approaches might be taken. Here, for example, are two very different ones:

1. Examine in considerable detail a particular episode in science, with attention to historical factors leading to the result and an analysis of the particular scientific arguments used, but without an attempt to cull from that any general "scientific method" or rules of reasoning.
2. Develop a general set of rules of reasoning to be used in scientific arguments, and then analyze one or more particular scientific episodes in terms of that generalized scientific method.

Historians of science tend to favor 1. Philosophers of science, including some scientists, tend to favor 2. Isaac Newton famously promulgated four general rules for investigating a scientific problem and then explicitly used them in arguing for his law of gravity.

If you want to see what makes particular cases of reasoning scientific, then 1 is quite limiting. What do the cases have in common that makes the reasoning different from that in nonscientific disciplines? But a potential danger of 2 is that the general scientific method produced either does not fit any actual episode well or is left so vague and uninformative that it seems to fit just about any attempt to reason, including nonscientific ones. The latter danger is what scientist and philosopher William Whewell found in Newton's four rules in the mid-19th century.

So a third approach suggests itself:

3. Declare that there are different scientific methods used by scientists on different occasions, depending on the problem to be solved and the information and techniques available to solve it. Examine a particular scientific episode in the manner of 1 above, but then analyze the reasoning used by means of some general rules that apply to this case and others, but by no means to all.

That, of course, leaves open the question of what, if anything, the methods in 3 have in common. But perhaps there are different legitimate scientific methods, just as there are different types of telescopes for investigating the heavens.

The problem I find in *How the Great Scientists Reasoned*, an otherwise fun read, is that Tibbetts can't really decide which approach to take. So, being eclectic, he tries a bit of the first two. Following 1, he dedicates chapters 3–9 to describing individual scientific episodes in some historical detail, without the benefit of any general set of rules or method that applies to all of them. Yet, in accordance with 2, he seems to think there is some general "scientific method." In chapters 2 and 10, rather than discussing any episodes, Tibbetts formulates a falsificationist version of the hypothetico–deductive method made famous by Karl Popper. But it is altogether too sketchy, and he barely employs it in analyzing particular cases. Since the scientific episodes he picks are quite different from each other, perhaps a useful strategy would have been 3. But, again, he does not propose or use any well-formulated methods of the sort required by 3.

Finally, I can't resist mentioning two great works on scientific methodology written by working scientists; I am confident Tibbetts would not find those presentations "as dry as dust and less gripping than a telephone directory." Both adopt strategy 2 above and carry it out with philosophical acumen and panache: *The Philosophy of the Inductive Sciences* (reprint, Routledge/Thoemmes Press, 1996), written by the aforementioned Whewell in 1840; and *The Aim and Structure of Physical Theory* (reprint, Princeton University Press, 1991), penned by Pierre Duhem at the beginning of the 20th century. I strongly recommend those books to the author and his audience.

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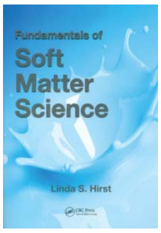
Fundamentals of Soft Matter Science

Linda S. Hirst
CRC Press, 2013. $79.95 (246 pp.).
ISBN 978-1-4398-2775-8

Soft matter is a class of materials with mechanical properties that lie between



those of elastic solids and viscous liquids. We encounter soft matter every day in the form of foods, pharmaceuticals, cosmetics, detergents, and digital displays. In fact, the tissues in our own bodies are biological soft materials. Soft materials are built from subunits larger than single molecules, and their overall structure and dynamics are governed by the interplay of thermal energy and the weak interactions of those subunits. The result is an extremely rich and fascinating phase behavior.

However, despite both the scientific interest in its varied behaviors and its technological importance, soft matter has been the subject of very few introductory textbooks. And fewer still cover the class's full range of materials, the relevant concepts and theoretical background, or the experimental techniques used to study them.

Linda Hirst's *Fundamentals of Soft Matter Science* is a welcome addition to that small list. The text aims at providing a comprehensive introduction to the science of soft materials. It is, as the author puts it, "designed for beginners to the field with a basic scientific background." The book is organized in five main chapters, each dedicated to a different class of soft matter: liquid crystals, surfactants, polymers, colloidal materials, and soft biomaterials.

It makes sense to organize an introductory text by focusing on those familiar material types. However, the book's organization underemphasizes the overarching principles that govern their behavior. Moreover, the book situates experimental techniques within subsections of the main chapters and thus associates them with specific categories of soft matter. In fact, all the techniques covered are used for many different types of soft matter, and I would have preferred that the techniques be linked to relevant physical mechanisms rather than to material types. Also, many of the experimental techniques are described too briefly for the reader to understand the underlying physical principles or interpret typical experimental results.

I recognize that the author had to make difficult choices in crafting an introductory text for such a highly multidisciplinary, diverse, and rich field of study. One dilemma she faced was to balance breadth and depth. On the one hand, a broad treatment would convey the field's richness and why it is a topic of fascination for researchers. On the other hand, it is important to go beyond superficiality and to convey an understanding of the underlying physical principles. *Fundamentals of Soft Matter Science* certainly succeeds in giving a broad overview and conveying the fascination of the field.

In my opinion, though, the book would have profited from a more detailed treatment of selected topics such as the experimental techniques, or of concepts such as phase separation or viscoelasticity. Fortunately, each chapter contains a sensible list of references that the reader can use to find more detailed information on the different topics.

Fundamentals of Soft Matter Science is not meant to be a reference book, but rather to provide a basic introduction to the field. I would expect it to be used in introductory undergraduate courses, but not as a main textbook in courses at the graduate or advanced undergraduate levels. The text should thus prove its worth to students new to soft-matter science and may also be useful more broadly to readers interested in obtaining a first overview of the field.

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From the Atomic Bomb to the Landau Institute

Autobiography. Top Non-Secret

Isaak M. Khalatnikov
(translated from Russian by Sergei Esipov and Yurii Morozov)
Springer, 2012. $69.95 (214 pp.).
ISBN 978-3-642-27560-9

The publication of a memoir by leading Russian physicist Isaak Khalatnikov, known as "Khalat" to his friends, is an event to be welcomed by anyone interested in 20th-century physics. The author was one of Lev Landau's first students before becoming his collaborator and senior associate. He was also the first director of the Landau Institute for Theoretical Physics, which he and his colleagues founded in 1964, two years after Landau had been in a tragic car accident. Khalatnikov led the institute for a quarter century.

From the Atomic Bomb to the Landau Institute: Autobiography. Top Non-Secret has two short chapters on Khalatnikov's childhood and early education. But it really takes off when he encounters Landau and Pyotr Kapitsa, the two giants who dominated the first half of his life. Kapitsa was the on-and-off director of the Institute for Physical Problems, where Landau and Khalatnikov worked until the end of Landau's career.

The narrative tells many stories about well-known and not so well-known figures in Russian science; the tales will be of interest primarily to readers who know something about their roles in the physics of their time. In the interest of full disclosure, I myself am not a distant bystander. I had the good fortune of spending the better part of the 1962–63 academic year—shortly after Landau's accident—as a postdoctoral fellow in Khalatnikov's theory group at the Institute for Physical Problems.

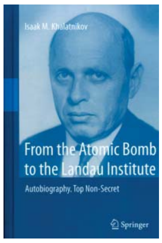
I found many tidbits to relish in Khalatnikov's memoir, particularly the descriptions of the many interactions of this self-described master of intrigue and manipulation with the Soviet bureaucracy and of his work with Landau on the Russian bomb mentioned in the book's title. But his overriding priority, Khalatnikov tells us, was the health and prosperity of the Landau Institute and the "Landau school" of theoretical physics. His encounters with the KGB and the influence of his past war work on his political fortunes, and even those of his daughter, make for entertaining, if puzzling, reading.

The personality of Landau, the "beloved teacher Dau," dominates the memoir, both before and after the tragedy of 1962. There have been many other accounts published of Landau's immense influence on his students, some of those by Khalatnikov himself, but this book is a good place to get a rounded picture of the man—his combination of benevolence and cruelty, of sophistication and naivety. One characteristic I had either forgotten about or had never known was that Landau never suggested research topics to his students, and he rarely helped them solve the problems they had chosen. In the few cases in which he did help, he would usually present his contributions as "gifts" to the deserving student without accepting coauthorship, since he set the bar very high to actually agree to have his name on a paper.

There are amusing and not so amusing anecdotes aplenty for those who know something about the atmosphere and culture of Soviet physics in the Cold War and post–Cold War eras. Examples are the descriptions of Landau's "theoretical minimum"—his famous entrance exam—and the weekly Landau seminars; the intrigue surrounding the founding of the Landau Institute and the election of Anatoly Aleksandrov to the presidency of the Soviet Academy of Sciences; and the reception in the Soviet Union of the Bardeen-Cooper-Schrieffer theory of superconductivity, especially the role played by Nikolai Bogoliubov.

After the establishment of the Landau Institute, one issue seems to have dominated most of the waking (and sleeping!) hours of many of the Soviet scientists and certainly those of the author: permission to travel abroad. We are treated to many examples of how that matter affected everyone, regardless of their standing in the hierarchy. A refreshing and rather touching, if somewhat fanciful, account of that period—in which Alexander "Sasha" Migdal refers to his time at the Landau Institute as "Paradise Lost"—is presented at the memoir's conclusion.

Throughout the book one notices Khalatnikov's attempts to tell it like it was and to avoid as much as possible the clichés of East and West. Nevertheless, one wonders what he is not telling us, either because he does not want us to know or because he does not want to explore the darkest sides of the story.



The subject of anti-Semitism is raised early in the book, but the word is not mentioned; it is referred to as "nationalism." Interestingly, Khalatnikov claims that outright anti-Semitism came rather late, in 1944, and originated with Joseph Stalin. I will leave it to others to evaluate that claim, but the issue might have deserved a fuller discussion, especially considering the many Jewish scientists who found a home in the Landau school.

The author hardly discusses the issue of refuseniks—scientists, primarily Jewish, who lost their jobs after applying for permission to emigrate—which affected the Landau Institute, and Khalatnikov personally. Also hardly mentioned is the plight of Andrei Sakharov, a matter in which the Soviet Academy of Sciences bears great responsibility. Curiously, Khalatnikov also does not mention that he accepted a faculty position at Tel Aviv University early in the post-Soviet era, even though he describes the terrible toll that brain drain took on Russian science and on the Landau Institute in particular. Finally, I must share my disappointment in the quality of the translation. (The Russian original was published in 2007.) It is difficult to believe that the translator is a native English speaker, given, for example, the number of missing and misplaced articles.

In spite of the above caveats, I thoroughly enjoyed *From the Atomic Bomb to the Landau Institute*. I believe that it will be of great interest to all those who have come into contact, either personally or through the literature, with the remarkable scientific achievements of Landau and the members of his school.

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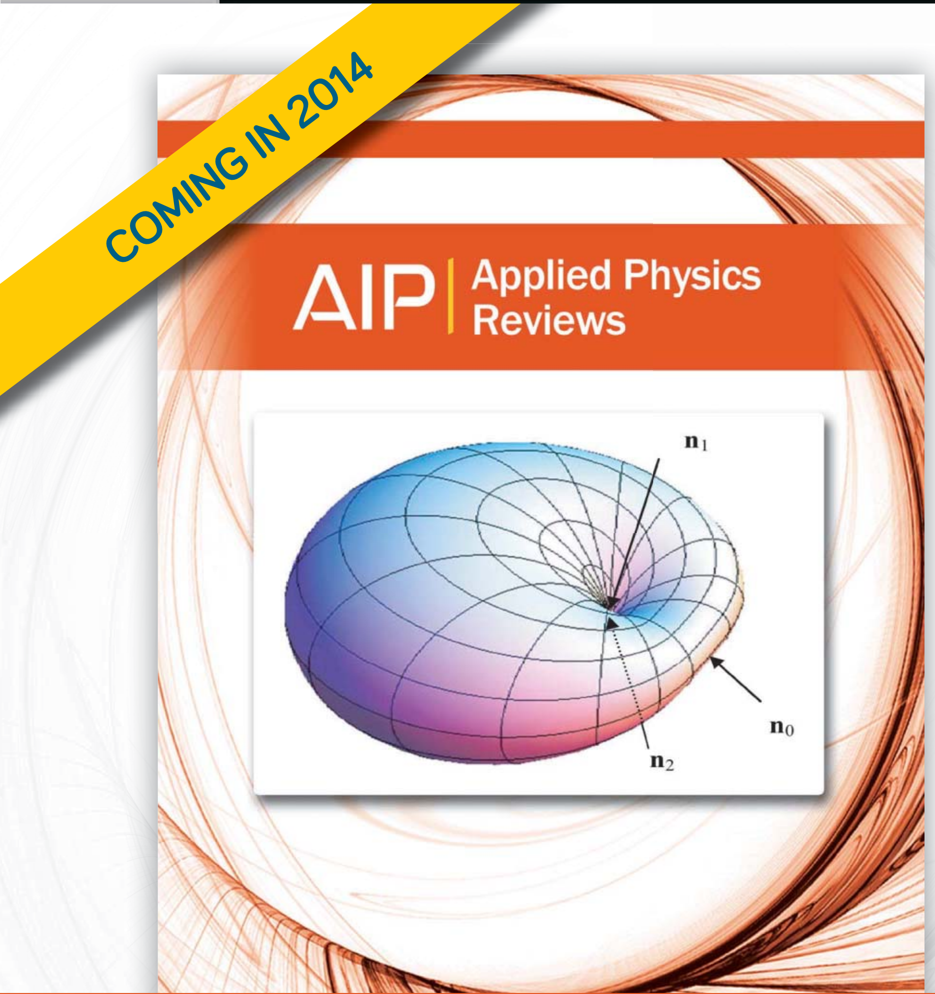
The Fractalist

Memoir of a Scientific Maverick

Benoit B. Mandelbrot
Pantheon Books, 2012. $30.00
(352 pp.). ISBN 978-0-307-37735-7

Before I first talked to Benoit Mandelbrot, my impression of him was shaped by reading his epic book, *The Fractal Geometry of Nature* (W. H. Freeman, 1982), which is not only ambitious and revolutionary, but formidable and serious. His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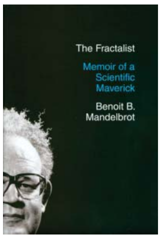

memoir *The Fractalist: Memoir of a Scientific Maverick* reflects the man I spoke to, a man enjoyed by his colleagues, friends, and mentees. It paints the picture of a man who was cultured, humorous, open-minded, and reflective.

Memoirs that look back on long and eclectic lives are often several books strung together, each capturing a distinct phase of the author's journey. Born in 1924 and still putting the final touches to his memoir when he died in 2010, Mandelbrot divided his 86-year tale into 3 parts. The reader doesn't need to have a specific interest in Mandelbrot or his research to enjoy each part. His experiences serve as windows into history, and his life's trajectory reveals how an influential career took shape.

In part 1, "How I Came to Be a Scientist," Mandelbrot begins with his childhood in depression-era Warsaw, Poland, and takes us through his experiences as a teenager in France during its occupation and liberation. Mixed in with his amazing adventures of escaping the Nazis, he tells of his early combat with mathematics: "I always started with a quick drawing. . . . This playful activity transformed impossibly difficult problems into simple ones. The needed algebra could always be filled in later." His childhood preference for pictures over equations emerged from a family talent for freehand drawing and went on to fuel his later discoveries of patterns in nature.

Part 2, "My Long and Meandering Education in Science and in Life," maps out an erratic early career spent criss-crossing from Paris to Caltech and back. Mandelbrot aspired to be a modern-day version of his hero, Johannes Kepler, by discovering "a degree of order in some real, concrete, and complex area where everyone else saw a mess."

Searching for major interdisciplinary challenges to conquer, Mandelbrot was painfully aware that some colleagues and relatives never forgave him for apparently squandering his mathematical talent on practical problems. How did he weather such criticism? "A blessing throughout my life: I never wonder who I am." Unrepentant about his quest to merge different fields, he came to accept that "scientific purists fear a new alloy."

Mandelbrot begins part 3, "My Life's Fruitful Third Stage," with his midlife-crisis move in 1958 to IBM's research division in Yorktown Heights, New York, and takes us through to his twilight. "I remember these years [1958–93] as a golden age—for IBM, for me, and for the sciences," he writes. "Let me go further, raise my voice and add: and also for the human spirit."

His adventure into fractal exploration began with a chance discovery. Invited to give a talk at Harvard University on patterns he'd explored in people's income, he saw a similar pattern in cotton price variations sketched on his Harvard host's blackboard. How could those two patterns be so similar? Soon after, he saw analogous patterns in the rise and fall of the Nile River and in the meandering coastline of Great Britain. By spotting the universal character of nature's patterns, he arrived at his "Kepler moment."

In 1975, Mandelbrot made his first attempt to catalog the rapidly expanding number of similar shapes found in nature by publishing a book with the tentative title, *Concrete Objects of Fractional Dimension*. A colleague advised him to liven up the title, so he introduced the term "fractal," which has since spread through many disciplines.

The title of one of his closing chapters lists the disciplines he journeyed through: "On to Fractals: Through IBM, Harvard, MIT, and Yale via Economics, Engineering, Mathematics, and Physics 1963–64." He acknowledges that "this chapter title seems to make no sense. . . . Very often when I listen to the list of my previous jobs, I wonder if I exist. The intersection of such sets is surely zero." When describing how his opportunistic character allowed him to cover such diverse ground, he cites Louis Pasteur's observation that chance favors the prepared mind. "Halfway through each discovery . . . I experienced a marvelous and exhilarating surprise" that triggered the next adventure.

Mandelbrot wrote *The Fractalist* to understand himself, so he deliberately waited until his final years to do so. "You have heard my story. Does not the distribution of my personal experiences remind me of the central topic of my scientific work—namely, extreme fractal unevenness?" We can all learn from the fractal unevenness found within these pages.

Richard Taylor
University of Oregon
Eugene

new books

atomic and molecular physics

Controlling Steady-State and Dynamical Properties of Atomic Optical Bistability. A. Joshi, M. Xiao. World Scientific, 2012. $92.00 (231 pp.). ISBN 978-981-4307-55-0

biological and medical physics

4th International Conference on Biomedical Engineering in Vietnam. V. V. Toi, N. B. Toan, T. Q. D. Khoa, T. H. L. Phuong, eds. Springer, 2013. $259.00 *paper* (407 pp.). ISBN 978-3-642-32182-5

Advances in Medical Physics 2012. Vol. 4. A. B. Wolbarst et al., eds. Medical Physics, 2012. $115.00 (330 pp.). ISBN 978-1-930524-56-9

Biologically Responsive Biomaterials for Tissue Engineering. I. Antoniac, ed. Springer, 2013. $129.00 (254 pp.). ISBN 978-1-4614-4327-8

Computational Systems Biology of Cancer. E. Barillot et al., eds. Chapman & Hall/CRC Press/Taylor & Francis, 2013. $79.95 (423 pp.). ISBN 978-1-4398-3144-1

Encyclopaedia of Medical Physics. Vol. 1: A–K. Vol. 2: L–Z. S.Tabakov et al., eds. CRC Press/Taylor & Francis, 2013. $719.00 *set* (822 pp. *set*). ISBN 978-1-4398-4652-0

International Symposium on Biomedical Engineering and Medical Physics. Y. Dekhtyar, A. Katashev, L. Lancere, eds. Springer, 2013. $259.00 *paper* (220 pp.). ISBN 978-3-642-34196-0

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Molecular Imaging of the Brain: Using Multi-Quantum Coherence and Diagnostics of Brain Disorders. M. M. Kaila, R. Kaila. Springer, 2013. $179.00 (385 pp.). ISBN 978-3-642-30301-2

Monte Carlo Calculations in Nuclear Medicine: Applications in Diagnostic Imaging. 2nd ed. M. Ljungberg, S.-E. Strand, M. A. King, eds. CRC Press/Taylor & Francis, 2013. $129.95 (337 pp.). ISBN 978-1-4398-4109-9

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Quantum Theory of Anharmonic Effects in Molecules. K. V. Kazakov. Elsevier, 2012. $150.00 (232 pp.). ISBN 978-0-12-397912-4

Visualization of Hydrogen-Bond Dynamics: Water-Based Model Systems on a Cu(110) Surface. T. Kumagai. Springer, 2012. $129.00 (145 pp.). ISBN 978-4-431-54155-4

computers and computational physics

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condensed-matter physics

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books

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Dark Matter, Neutrinos, and Our Solar System. N. Prakash. World Scientific, 2013. $133.00 (700 pp.). ISBN 978-981-4304-53-5

IX Workshop of the Gravitation and Mathematical Physics Division of the Mexican Physical Society. L. A. Ureña-López, R. Bercerril-Bárcenas, R. Linares-Romero, eds. AIP, 2012. $141.00 *paper* (270 pp.). ISBN 978-0-7354-1080-0

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energy and environment

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fluids

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2nd International Advances in Applied Physics and Materials Science Congress. M. H. Aslan, A. Y. Oral, eds. AIP, 2012. $159.00 *paper* (408 pp.). ISBN 978-0-7354-1085-5

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The Handbook on Optical Constants of Semiconductors: In Tables and Figures. S. Adachi. World Scientific, 2012. $188.00 (619 pp.). ISBN 978-981-4405-97-3

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Nanostructures and Nanoconstructions Based on DNA. Y. M. Yevdokimov, V. I. Salyanov, S. G. Skuridin. CRC Press/Taylor & Francis, 2012. $139.95 (250 pp.). ISBN 978-1-4665-0569-8

Structure of Materials: An Introduction to Crystallography, Diffraction and Symmetry. 2nd ed. M. De Graef, M. E. McHenry. Cambridge U. Press, 2012. $115.00 (739 pp.). ISBN 978-1-107-00587-7

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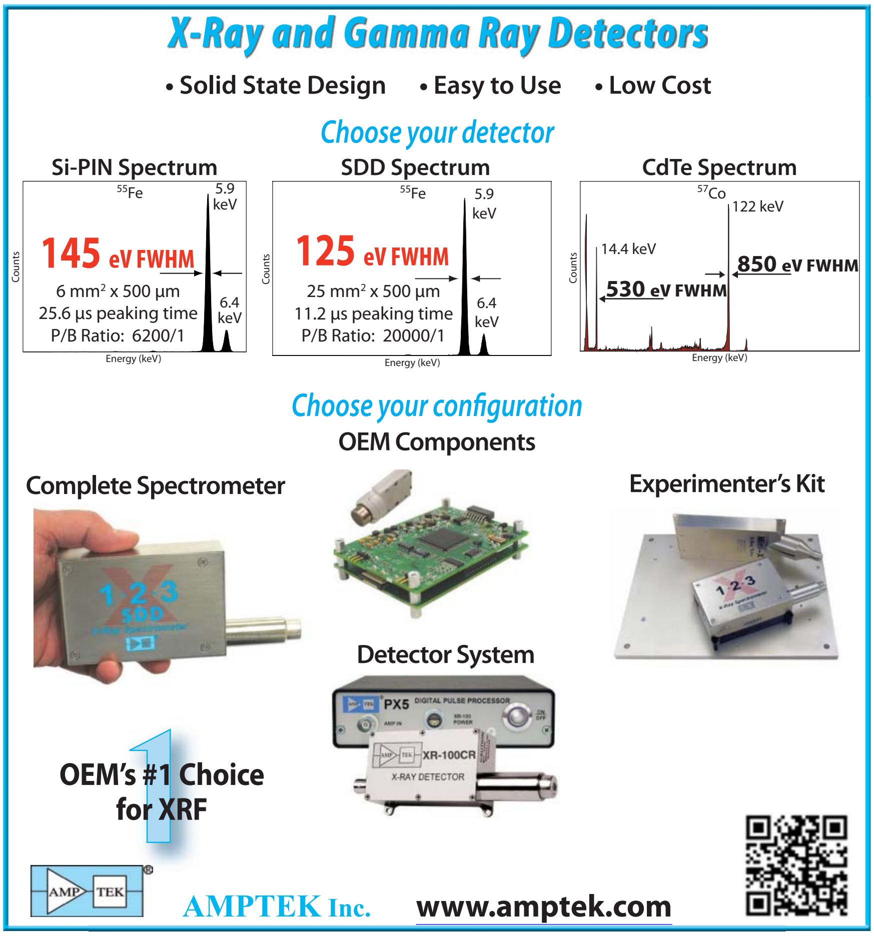

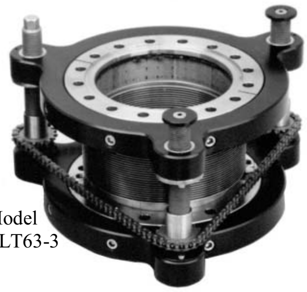

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eds. AIP, 2012. $150.00 (280 pp.). ISBN 978-0-7354-1079-4

nonlinear science and chaos

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particle physics

Flavor Physics at the Tevatron: Decay, Mixing and CP-Violation Measurements in $p\bar{p}$-Collisions. T. Kuhr. Springer, 2013. $159.00 (172 pp.). ISBN 978-3-642-10299-8

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Gauge Theories in Particle Physics: A Practical Introduction. Vol. 2: Non-Abelian Gauge Theories; QCD and the Electroweak Theory. 4th ed. I. J. R. Aitchison, A. J. G. Hey. CRC Press/Taylor & Francis, 2013. $69.95 (518 pp.). ISBN 978-1-4665-1307-5

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Massive: The Missing Particle That Sparked the Greatest Hunt in Science. I. Sample. Basic Books, 2012. $16.99 *paper* (304 pp.). ISBN 978-0-465-05873-0

Mathematics: An Illustrated History of Numbers. T. Jackson, ed. Shelter Harbor Press, 2012. $24.95 (144 pp.). ISBN 978-0-9853230-4-2

The Mathematics of Life. I. Stewart. Basic Books, 2012. $15.99 *paper* (368 pp.). ISBN 978-0-465-03240-2

National Geographic Angry Birds Furious Forces! The Physics at Play in the World's Most Popular Game. R. Allain. National Geographic, 2013. $13.95 *paper* (160 pp.). ISBN 978-1-4262-1172-0

Total Addiction: The Life of an Eclipse Chaser. K. Russo. Springer, 2012. $24.95 *paper* (193 pp.). ISBN 978-3-642-30480-4

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quantum physics

The Conceptual Framework of Quantum Field Theory. A. Duncan. Oxford U. Press, 2012. $120.00 (782 pp.). ISBN 978-0-19-957326-4

Introduction to Quantum Mechanics: Schrödinger Equation and Path Integral. 2nd ed. H. J. W. Müller-Kirsten. World Scientific, 2012. $88.00 *paper* (919 pp.). ISBN 978-981-4397-74-2

Physics in Mind: A Quantum View of the Brain. W. R. Loewenstein. Basic Books, 2013. $28.99 (325 pp.). ISBN 978-0-465-02984-6

Quantum Africa 2010: Theoretical and Experimental Foundations of Recent Quantum Technology. E. Brüning, T. Konrad, F. Petruccione, eds. AIP, 2012. $124.00 *paper* (132 pp.). ISBN 978-0-7354-1076-3

Quantum Field Theories in Two Dimensions: Collected Works of Alexei Zamolodchikov. Vols. 1 and 2. A. Belavin, Y. Pugai, A. Zamolodchikov, eds. World Scientific, 2012. $178.00 (1045 pp.). ISBN 978-981-4324-06-9 ■

new products

Focus on materials

The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. PHYSICS TODAY can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of the product description.

Andreas Mandelis

Contact resonance viscoelastic mapping

The contact resonance (CR) viscoelastic mapping mode is an option Asylum Research now offers exclusively for its Cypher and MFP-3D atomic force microscopes. Some other nanomechanical imaging techniques measure only the elastic modulus of materials, not the loss modulus. However, both the elastic and dissipative responses are critical to the performance of many modern materials. CR enables high-resolution, quantitative imaging of both elastic storage and viscoelastic loss moduli. The technique is suitable for characterizing moderate- to high-modulus materials—composites, thin films, biomaterials, polymer blends, and even ceramics and metals—in the range of about 1 GPa to 200 GPa. According to Asylum, its hardware and software developments have made CR imaging faster, more quantitative, simpler to use, and applicable to a wider range of materials. *Asylum Research, 6310 Hollister Avenue, Santa Barbara, CA 93117, http://www.asylumresearch.com*

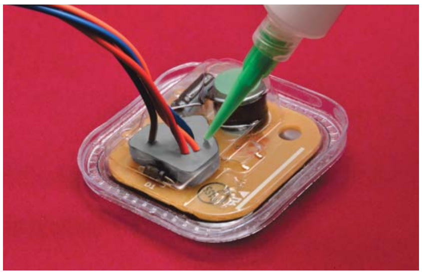
Fused-silica melting vessels

Excellent thermal and chemical stability make fused silica a popular choice of melting vessel material, so it can be used with materials that may be subject to rapid temperature changes during processing. However, some manufacturing methods can yield inconsistent vessels, which can result in a reduced vessel lifetime or failure during the

melting process. To overcome those shortcomings, Goodfellow molds its high-purity, fused-silica melting vessels. Features include seamless one-piece construction of fully dense material; a uniform microstructure with isotropic properties; and a nonporous, unreactive internal surface to easily remove melted material. Goodfellow offers the vessels in a wide range of sizes and capacities. Shapes include square, cylindrical, and rectangular. *Goodfellow Corporation, 125 Hookstown Grade Road, Coraopolis, PA 15108-9302, http://www.goodfellow-ceramics.com*

Thermally conductive flame-retardant epoxy

A two-part silicone system, Master Bond's MasterSil 156 is addition cured and does not require exposure to air for complete cross-linking. It has a convenient one-to-one mix ratio by weight and



will not outgas while curing. Formulated for potting, encapsulation, and sealing applications, MasterSil 156 is a good electrical insulator with a low viscosity that can cure in sections beyond 2.5–5 cm thick. It is thermally conductive, and Underwriters Laboratories has temperature rated it to 105 °C in thicknesses 0.64 cm or larger. Its flexibility allows it to withstand aggressive thermal cycling and resist vibration and shock. It is resistant to water, humidity, oils, and other environmental elements and has passed the rigorous UL 94V-0 tests for flame retardancy. MasterSil 156 bonds well to various substrates, including metals, composites, glass, ceramics, and many rubbers and plastics. *Master Bond Inc, 154 Hobart Street, Hackensack, NJ 07601, http://www.masterbond.com*

Semiconductor defect review system

Park Systems has introduced Park NX-HDM, a fully automated defect review and subangstrom surface roughness atomic force microscopy system for device substrates and disk media. It analyzes, identifies, and scans media for all wafer sizes up to 150 mm. According to the company, the system increases

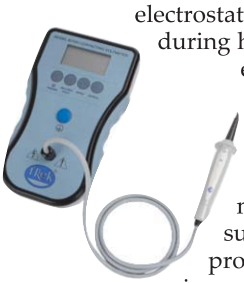
throughput up to 1000% and offers a 30% higher success rate than prior systems. Suitable for the hard disk drive, LED, solar, and general semiconductor device industries, the NX-HDM speeds up the automatic defect review for media and substrates. The survey scan, zoom-in scan, and analysis of imaged defect types are automated with a wide range of optical inspection tools. Combined with the low noise floor, the true noncontact mode provides accurate and reliable measurements for the subangstrom surface roughness of diverse media and substrates. *Park Systems Inc, 3040 Olcott Street, Santa Clara, CA 95054, http://www.parkafm.com*

Dry particle counter

The ADPC 302 from Pfeiffer Vacuum is an in-process management system for particle contamination monitoring in semiconductors. It measures the number of particles in wafer transport carriers—that is, front-opening unified pods and front-opening shipping boxes. The fully automated, patented process localizes and counts particles from the carrier surfaces, including the door. Submicrometer particles can cause defects that can lead to considerable yield loss; even particles measuring 0.1 µm may damage the structure of semiconductor chips. The system can be used for both serial production and R&D analysis. The main applications are carrier characterization, cleaning strategy optimization, and cleaning quality checks. The test time is only seven minutes, which makes the ADPC 302 four times as fast as traditional systems. It is possible to test eight transport carriers in one hour. *Pfeiffer Vacuum Inc, 24 Trafalgar Square, Nashua, NH 03063-1988, http://www.pfeiffer-vacuum.com*

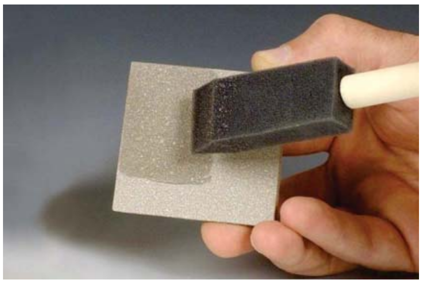
Electrostatic voltmeter for materials research

With model 821HH, Trek expands its Infinitron ultrahigh impedance voltmeter technology. It performs effective contacting measurement—without charge transfer—of site-specific voltage on devices and materials sensitive to electrostatic discharge (ESD) during handling and processing. There is no charge transfer because the probe tip assumes the voltage level of the measured object's surface as the tip approaches and results in no current flow at the time of contact and therefore no change in surface potential. The unit can be used to measure both conductive and insulating surfaces. Applications for model 821HH include semiconductors, photovoltaics, LEDs and other electronic devices, and materials research. According to Trek, the new technology may enable advancements in surface characterization and ESD prevention and control. *Trek Inc, 190 Walnut Street, Lockport, NY 14094, http://www.trekinc.com*



High-temperature sealant

Aremco-Seal 529 is an advanced, single-part, optically clear silicone coating for components and substrates used in applications to 600 °F. Up to that temperature, Aremco-Seal 529 is optically stable, noncrazing, and impermeable to moisture. It is also resistant to a wide range of chemicals and provides a high dielectric strength of 350 V/mil. It is suitable for sealing microelectronic substrates, printed circuit boards, electrical connectors, pyrolytically deposited films, ceramic-filled cartridge heaters,



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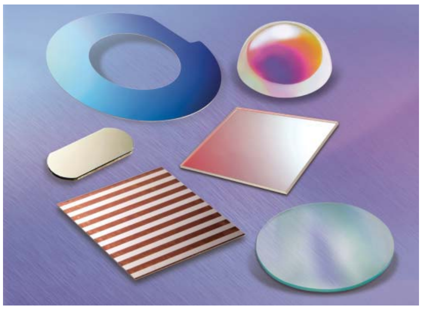

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new products

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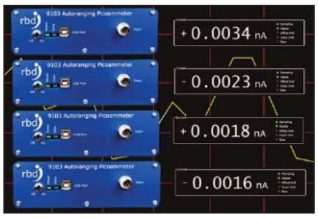

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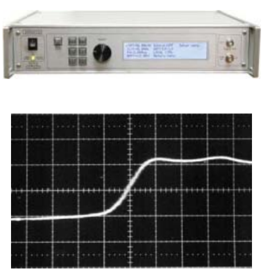

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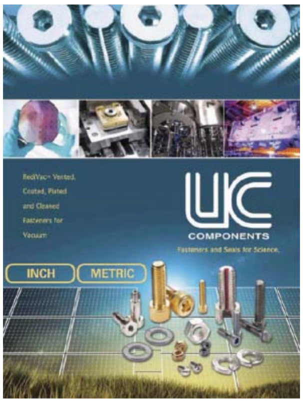

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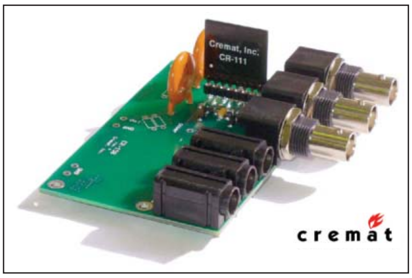

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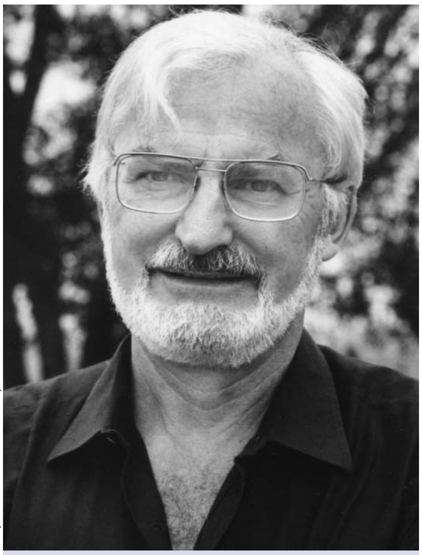
Heinrich Rohrer



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Heinrich Rohrer

Heinrich Rohrer, Heini to his friends, passed away in Wollerau, Switzerland, on 16 May 2013, three weeks short of his 80th birthday. He has been called the father of nanotechnology, and he helped establish the field with the invention, along with Gerd Binnig and Christoph Gerber, of the scanning tunneling microscope (STM). For their work, Heini and Binnig shared half the 1986 Nobel Prize in Physics. The other half went to Ernst Ruska for the much earlier invention of the electron microscope.

Heini inspired many of us to get into nanotechnology. Perhaps most important, he guided the nascent field with his extraordinary wisdom. I remember him telling a group of us working on scanning probe microscopy that we could praise our own inventions to the high heavens, but that the trouble starts if we bad-mouth someone else's inventions! In particular, he advised us to stay away from comparisons of our new scanning probe microscopes (SPMs) with electron microscopes. He said the problem is the temptation to compare our new, state-of-the-art instrument to an existing commercial one that may be using 20-year-old technology rather than what's state of the art in that field.

To those of us entering nanotech, Heini gave advice freely and provided substantial assistance. He helped the biophysics lab at the University of California, Santa Barbara, get started by sending it his first STM postdoc, Othmar Marti, for a year at the expense of IBM, Heini's employer. He strongly encouraged innovation and the development of other SPMs. He frequently noted that as long as an SPM was different enough from existing ones, a use would be found for it. That has proved true: For example, even though scanning capacitance microscopes and scanning ion conductance microscopes have very poor resolution compared with the STM, they are useful because they are sensitive to things beyond topography.

Heini was born on 6 June 1933 in the small town of Buchs in Switzerland. He studied physics at ETH Zürich, where he was an undergraduate under Wolfgang Pauli and Paul Scherrer. He stayed on to obtain his PhD, on the length changes of superconductors at the magnetic-field-induced superconducting transition, with Jørgen Lykke Olsen. As Heini wrote in his Nobel Prize biography, "Following in [Olsen's] footsteps, I lost all respect for angstroms. The mechanical transducers were very vibration sensitive, and I learned to work after midnight, when the town was asleep." That was important background for the invention of the STM, since measuring small distances in the presence of vibrations is crucial.

In the summer of 1963, Ambros Speiser, director of the newly founded IBM Research Laboratory in Rüschlikon, Switzerland, invited Heini to join the physics effort there. Heini first worked on Kondo systems with magnetoresistance in pulsed magnetic fields and then on other magnetic systems. The real excitement started in 1978 when he hired Binnig, a genius who soon began work on what would become the STM. Heini had the good sense to give Binnig the freedom he needed to explore an area that was new to them both and totally unproven.

Later Heini had the foresight to foster the transition of STM technology beyond IBM into the world. At first it seemed to many others that it would be impossible to enter that area. After all, the creative minds working at IBM had a budget in the millions for making complex devices that depended on magnetic levitation in ultrahigh vacuum at cryogenic temperatures. What academic researcher could hope to compete? But Heini was persistent in encouraging others to join the field. And, as it turned out, useful STMs could be made without magnetic levitation, without ultrahigh vacuum, and at room temperature.

Although STMs in ultrahigh vacuum at cryogenic temperatures continue to give spectacular results, other SPMs have proved useful for technological and medical research in air or fluids at room temperature. The rapid and friendly spread of the technology is due in large part to the spirit of the field established by Heini: collaboration, cooperation, and mutual respect.

Paul Hansma
California NanoSystems Institute
University of California, Santa Barbara

Kenneth Geddes Wilson

Physics lost a creative genius on 15 June 2013, when Kenneth Geddes Wilson died at age 77 in Saco, Maine, of complications from lymphoma.

Leo Kadanoff, one of many physicists who inspired Ken, wrote after his death, "Ever since the early 1970s, the tools and concepts put forward by Wilson have formed the very basis of particle physics, field theory, and condensed matter physics. These concepts included fixed points, couplings that vary with scale, variation of physical properties with spatial dimension, description of couplings via anomalous dimension, qualitative variation in properties as a consequence of phase transitions, and topological descriptions of excitations."

Ken was born on 8 June 1936 in Waltham, Massachusetts. His father, accomplished Harvard University chemist E. Bright Wilson, was a student of Linus Pauling; his father and Pauling coauthored an influential early text on quantum mechanics. His mother was a physics graduate student before marrying. Ken was a member of the first generation to grow up with quantum mechanics, and he had an exceptional perspective.

As an undergraduate at Harvard, Ken was a Putnam fellow in 1954 and 1956. He also ran the mile on the varsity track team. After receiving his BA in physics in 1956, he was advised by his father to study under Richard Feynman or Murray Gell-Mann in graduate school at Caltech. According to Ken, Feynman said he wasn't working on anything, so Ken began his effort to make sense of strongly interacting field theories under Gell-Mann and received a PhD in 1961.

Ken was a junior fellow of the Harvard Society of Fellows from 1959 to 1962. He spent a year at CERN and then in 1963 joined the faculty at Cornell University, where he spent 25 remarkable years. He famously obtained tenure in two years with virtually no real publication record. By his own account, he had sought problems so difficult that publications would be few. He proceeded to reshape our understanding of quantum field theories and to tremendously extend their utility.

For more than 10 years, Ken employed pion–nucleon scattering and fixed-source theory as paradigms for nonperturbative renormalization. He did not try to tailor his work to any specific problem but instead sought tools sufficiently powerful to solve whole classes of problems, and he took inspiration from nonrelativistic quantum mechanics, which offers reliable nonperturbative methods. In 1965 he introduced many key features of his renormalization group approach, but he did not solve the fixed-source problem. He realized that he must allow for an arbitrarily large number of couplings, the hallmark of the Wilsonian renormalization group. After another five years, during which he invented the operator product expansion, Ken solved a drastically truncated version of the problem numerically, with controlled errors. Few appreciated what he had accomplished, but he then made rapid progress on many fronts.

Ken continued to work on renormalization of the strong interaction throughout his career. He investigated almost all possible asymptotic scaling behavior of the strong coupling in 1971, but he missed asymptotic freedom because, by his account, he had not taken gauge invariance seriously enough. That work led him in 1974 to invent lattice gauge theory, which grew into a subfield in particle physics and has evolved to become the most reliable tool for nonperturbative calculations in quantum chromodynamics.

While Ken was working on his fixed-source calculations through the 1960s, the subject of phase transitions came to his attention. Inspired by Benjamin

Kenneth Geddes Wilson

Widom and Kadanoff, he realized that phase transitions require a large range of coupled length scales, exactly the sort of problem he was encountering in quantum field theory. He began an extremely fruitful collaboration with Michael Fisher at Cornell. Their seminal work on critical points and phase transitions revolutionized condensed-matter theory, especially after the epsilon expansion provided examples of Ken's ideas that could be computed analytically rather than numerically.

In 1975 he published his Kondo-problem solution, which exploited its similarity to the fixed-source problem he had solved. He included a lucid discussion of the deep connections between renormalization problems in condensed-matter physics and particle physics, a bridge that led to incredibly fruitful collaborations between the two fields. The reach of effective field theory grew to cover all scales.

In 1982 Ken received the Nobel Prize in Physics for his development of general and tractable renormalization group methods to handle widely different scales of length simultaneously. Such problems include some of the most difficult and important in physics, among them critical points and phase transitions.

Fascinated by computers as a graduate student, Ken soon considered them as essential as analytic techniques for his calculations. He became a champion of computational physics and supercomputers, with lattice gauge theory pushing their limits for decades. In 1985 he was appointed director of the Cornell Theory Center (now the Center for Advanced Computing), one of the first supercomputing centers created by NSF.

In 1988 Ken moved to the Ohio State University. His wife, Alison Brown, had been hired by Ohio State's supercomputer center; Ken liked to joke that he was a spousal hire. He wanted to turn his attention to education, and at Ohio State he could establish a physics education research group. He served as a codirector for Project Discovery, a statewide effort to improve science education, but his attention naturally drifted to education as a whole. Working with Constance Barsky, he mounted a monumental effort to find practical means to drastically improve the US educational system, including studying fields as disparate as geology and airplane engineering for productive analogues. His efforts were still nascent at the time of his death, but his 1994 book *Redesigning Education* (Holt), written with Bennett Daviss, outlined many of his basic ideas.

Ken continued to work on the strong interaction at Ohio State, and he developed a novel alternative to lattice gauge theory that employs Dirac's light-front formulation of field theory. In the process of developing renormalization group tools for that problem, Stanislaw Glazek and Ken invented the similarity renormalization group. Its transformations are designed to avoid problems in Ken's earlier transformations and hopefully extend the reach of the renormalization group.

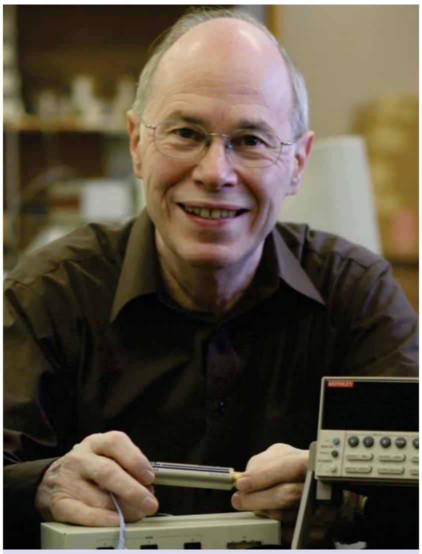
Ken was generous with his time and his ideas. He delighted in helping students. At times, it seemed as if he thought in his own language, and when anyone had difficulty understanding his ideas, he would patiently translate them into a more accessible form.

No account of Ken should omit his other passions: hiking, kayaking, and folk dancing. And the gardens he grew with Alison were amazing.

Robert Perry
Ohio State University
Columbus

Paul William Zitzewitz

Paul William Zitzewitz, a dedicated educator, noted textbook author, atomic physicist, and leader in the American Association of Physics Teachers (AAPT), passed away on 30 April 2013 in Northville, Michigan,



Paul William Zitzewitz

at age 70 after a long battle with cancer.

Paul was born in Chicago on 5 June 1942. While in high school, he developed a strong interest in science and had an early internship with IBM in downtown Chicago. After earning his BA in physics from Carleton College in Minnesota in 1964, Paul went to Harvard University and received his AM and PhD in physics in 1965 and 1970, respectively.

Under the guidance of Nobel laureate Norman Ramsey, Paul did his thesis work on the atomic hydrogen maser. He focused on measuring the frequency shifts arising from collisions of the hydrogen atoms with the maser walls. That work led to a significant improvement in the accuracy of our knowledge of the maser transition frequency and to the maser's use as a fundamental time standard. Paul's wide-ranging curiosity led him, even as a graduate student, to think about the recently discovered millisecond-period pulsars as possible time standards.

Between 1970 and 1972, Paul was a postdoc at the University of Western Ontario in Canada. He then spent a year at Corning Glass Works as a senior research scientist before being hired in 1973 as an assistant professor of physics at the University of Michigan-Dearborn. In 1978 he became an associate professor of physics, and in 1984, a professor.

In his research at Dearborn, Paul concentrated on positrons and positronium. With colleagues at the University of Michigan in Ann Arbor, he made precision measurements of the decay rate of ortho-positronium.

A dedicated teacher, Paul had several noteworthy achievements during his long career, including his reforms of upper-division laboratory, electronics, and advanced laboratory courses. For both in-service and pre-service elementary school teachers, he developed and taught three courses on science education. In recognition of his accomplishments in education, he was appointed a professor of science education in 2005. Paul served as chair of the department of natural sciences from 1999 to 2005 and associate dean of the College of Arts, Sciences, and Letters from 1988 to 1993. In 2009 he retired from his faculty positions.

Paul's *Physics: Principles and Problems* (McGraw-Hill/Glencoe, 2005) is a widely used high school textbook that has gone through nine editions and has been translated into several foreign languages. He also authored the second edition of *The Handy Physics Answer Book* (Visible Ink Press, 2011), which presents physics phenomena in easy-to-understand conceptual language for the general public.

Paul was active in many physics and physics teachers' organizations, including AAPT and the Detroit Metropolitan Area Physics Teachers. He served as president of AAPT's Michigan section in 1996–97 and as treasurer and executive board member of the national AAPT from 2008 until his death. With the American Physical Society, Paul served on the Committee on Education and the Committee on Informing the Public, and he was chair of the Forum on Education in 1998–99. He received the distinguished service award from AAPT's Michigan section in 2001. Among Paul's many recognitions from the University of Michigan-Dearborn were the Distinguished Faculty Research Award in 1985 and the Distinguished Teaching Award in 2007.

Being dedicated to K–12 education, in 2010 Paul and his wife, Barbara, generously endowed AAPT's Excellence in Pre-College Teaching Award, now the Paul W. Zitzewitz Award for Excellence in Pre-College Physics Teaching.

Throughout his life, Paul enthusiastically shared with his colleagues, students, children, and grandchildren his curiosity about the natural world; his love of scientific research, teaching, and learning; and his engaging sense of humor.

Robert C. Hilborn
American Association of Physics Teachers
College Park, Maryland ■

quick study

Swimming in the desert

Yang Ding, Chen Li, and Daniel I. Goldman

Physicists and colleagues from various disciplines are just beginning to study how organisms and robots move within and on granular media. An old theory from fluid mechanics can help guide them.

Yang Ding is a postdoc at the University of Southern California in Los Angeles. **Chen Li** is a postdoc at the University of California, Berkeley. **Daniel Goldman** is an associate professor of physics at the Georgia Institute of Technology in Atlanta.

Locomotion, the movement of a body from place to place via self-deformation and interaction with an environment, is so ubiquitous in the natural world that many people don't give it a second thought. But locomotion challenges scientists to understand the dynamics of biological and physical systems. Furthermore, the substrates that animals move within—examples include air, water, sand, and mud—can be deformable; for the cases of sand and mud, scientists still don't have a fundamental description of substrate rheology. Organisms have an enormous number of degrees of freedom, and their numerous muscles, tendons, and skeletal elements are hierarchically organized and controlled by complex nervous systems. Despite those complexities, biologists, mathematicians, engineers, and physicists have made great strides in understanding movement.

Traditionally, movement on rigid ground or in flowing fluids like air and water has been scientists' focus. But many terrestrial animals move on the surface of and even within substrates that are neither ideal solids nor ideal fluids. One such substrate is sand. Like other granular media, sand is a collection of solid particles that interact through dissipative, repulsive contact forces. Granular media can flow as fluids do, but they can also hold their shape like solids. Sand, in particular, is home to many arachnids, reptiles, and mammals that run rapidly across its surface to hunt for prey. Some, such as the sandfish lizard shown in figure 1, even dive into sand and move within it to escape heat and predators.

A look below the surface

Despite hundreds of years of study, scientists do not yet have a comprehensive understanding of the flow and effective solidification of granular media subject to intrusion by a body or leg. One reason is the complexity of grain response to localized forces. For example, granular materials can support loads through the formation of complex force-chain networks, exhibit compressible flow with heterogeneous regions of density and pressure, or even act like gases described by the kinetic theory. (For more, see the article by Anita Mehta, Gary Barker, and Jean-Marc Luck, PHYSICS TODAY, May 2009, page 40, and the Quick Study by Jackie Krim and Bob Behringer, PHYSICS TODAY, September 2009, page 66.)

Figure 1. The sandfish is native to north Africa and the Middle East. (Courtesy of John Toon.)

In 2009 Ryan Maladen and the three of us performed the first detailed explorations of locomotion within granular media; as shown in figure 2a, we used high-speed x-ray imaging to record the movement in sand of a 10-cm-long lizard, the sandfish *Scincus scincus*. In those experiments we discovered that when it is below the surface, the lizard tucks its legs to its sides and swims forward by means of a sinusoidal body undulation traveling from head to tail. We were surprised to discover that the wave shape resembled that of the smaller, 1-mm-long nematode worm *Caenorhabditis elegans* swimming in a viscous fluid. However, the forward speed of the sandfish in body lengths per second was greater than that of *C. elegans*. Furthermore, the sandfish moved nearly 0.4 body lengths per undulation, double the rate achieved by *C. elegans*.

In trying to explain those observations, we faced a problem: We had no means to calculate the interaction of the sandfish with the granular medium. Further, we didn't know if the animal was swimming in a solid, a fluid, or a complex combination of both. In part because the sandfish looked so much like *C. elegans*, we posited that the granular medium surrounding a continuously moving locomotor would behave like a fluid. With nothing else to try, we appealed to an old theory from fluid mechanics.

A sandfish superposition principle

The partial differential equations describing fluid motion—the Navier–Stokes equations—are complex and nonlinear. So for more than 60 years, researchers have used a simplified theoretical approach called resistive force theory (RFT) to model undulatory and flagellar propulsion in fluids at low Reynolds number *Re*—that is, for motion in which inertial forces are small relative to viscous forces. The theory, introduced by G. I. Taylor and by James Gray and G. J. Hancock, is based on the assumption that the forces $F_\perp$ and $F_\parallel$ acting perpendicular and parallel to the axis of an infinitesimal body element are independent of the position and movement of other body elements. Note that the ratio of $F_\perp$ to $F_\parallel$, the so-called drag anisotropy, must be greater than unity for forward propulsion. At low *Re*, the inertial terms in the Navier–Stokes equations can be neglected, and thus, at constant swimming speed, the sum of all the independent, superposed forces on the organism vanishes. Given that simplification, one can calculate swimming speeds in terms of, for example, the speed at which the undulation travels down the organism.

To do the calculation, one needs to know how $F_\perp$ and $F_\parallel$ depend on the orientation, relative to the movement direction, of a submerged body such as a cylinder (see figure 2b). For low *Re* fluids, those forces can be calculated theo-

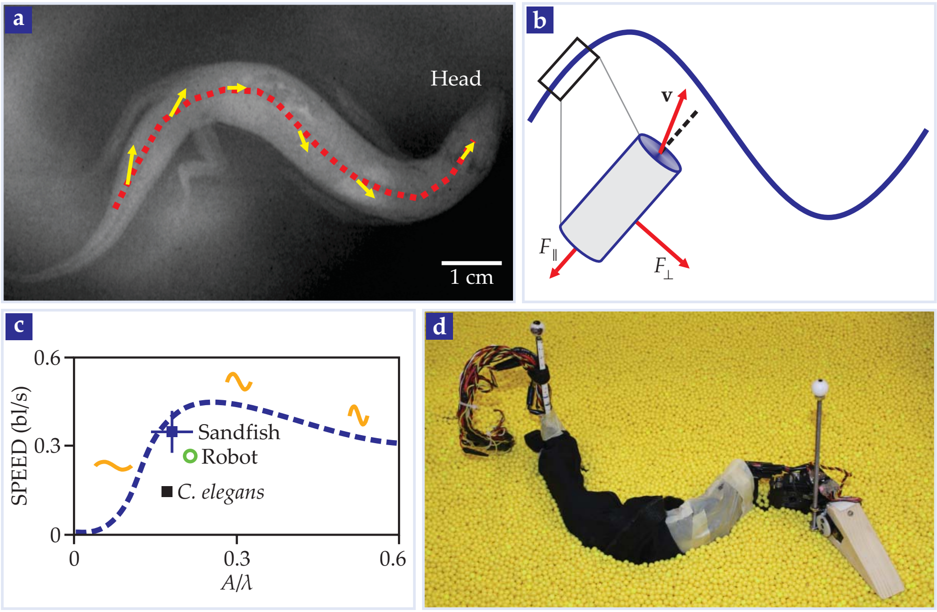


Figure 2. Locomotion within dry granular media. **(a)** This top-view x-ray snapshot shows a sandfish lizard swimming in a medium of small glass particles. Yellow arrows are estimates of the velocity of small elements of the sandfish based on resistive force theory. The overall motion is to the right. (Courtesy of Sarah Sharpe.) **(b)** In RFT, the forces on organism elements are assumed to be independent; here an element is represented as a cylinder. One needs to know how the forces parallel ($F_\parallel$) and perpendicular ($F_\perp$) to the cylinder axis depend on the orientation of the cylinder relative to its velocity **v**. **(c)** Swimming speeds in body lengths per second are shown for the sandfish, the 55-cm-long robot seen in **(d)**, and the worm *Caenorhabditis elegans*, as a function of the amplitude (A) and wavelength (λ) indicated by the yellow curves. The sandfish achieves almost the optimal motion predicted by RFT (dashed curve). (Panel c adapted from R. D. Maladen et al., *J. R. Soc. Interface* **8**, 1332, 2011.)

retically. But for our study of motion in a granular medium, we introduced a cylinder to represent a small element of the sandfish's body and determined the forces experimentally.

We discovered some interesting ways in which horizontal drag forces in granular media differ from those for low *Re* motion in fluids. For example, at low *Re*, fluid forces are proportional to speed, but in granular media, forces are insensitive to speed—at least at the speeds of 50 cm/s or less that are characteristic of sandfish locomotion. The reason for the constancy is that for sandfish-speed motion in granular media, particle inertia is negligible; forces result mainly from friction between body elements and the particles around them and from particle–particle friction. Here's another interesting difference: In fluids, horizontal drag forces on a small body are independent of the body's depth beneath the surface, but in granular media, such forces are proportional to depth because of a hydrostatic-like pressure.

We found similar behavior for $F_\parallel$ as a function of the orientation of the cylinder axis relative to the velocity when we looked at motion in granular media and at low *Re* motion in fluids. But the behavior of $F_\perp$ was different; in granular media, the force rose more rapidly at shallow angles of attack (small angles separating cylinder axis and velocity). The mechanism underlying that different behavior is unclear, but we hypothesize that it is related to a solid-like pileup of grains near the surface.

An efficient swimmer

When we summed all the forces acting on the sandfish and set that sum to zero, we were surprised to find that RFT predicted the speed of the animal to within 20%. The agreement indicates that our picture of a sandfish swimming in a granular fluid is reasonable; later simulations revealed that the fluid is localized to a small region around the body. Moreover, RFT showed that the larger $F_\perp/F_\parallel$ in granular media accounted for the fact that the sandfish advances a greater number of body lengths per undulation than does *C. elegans*.

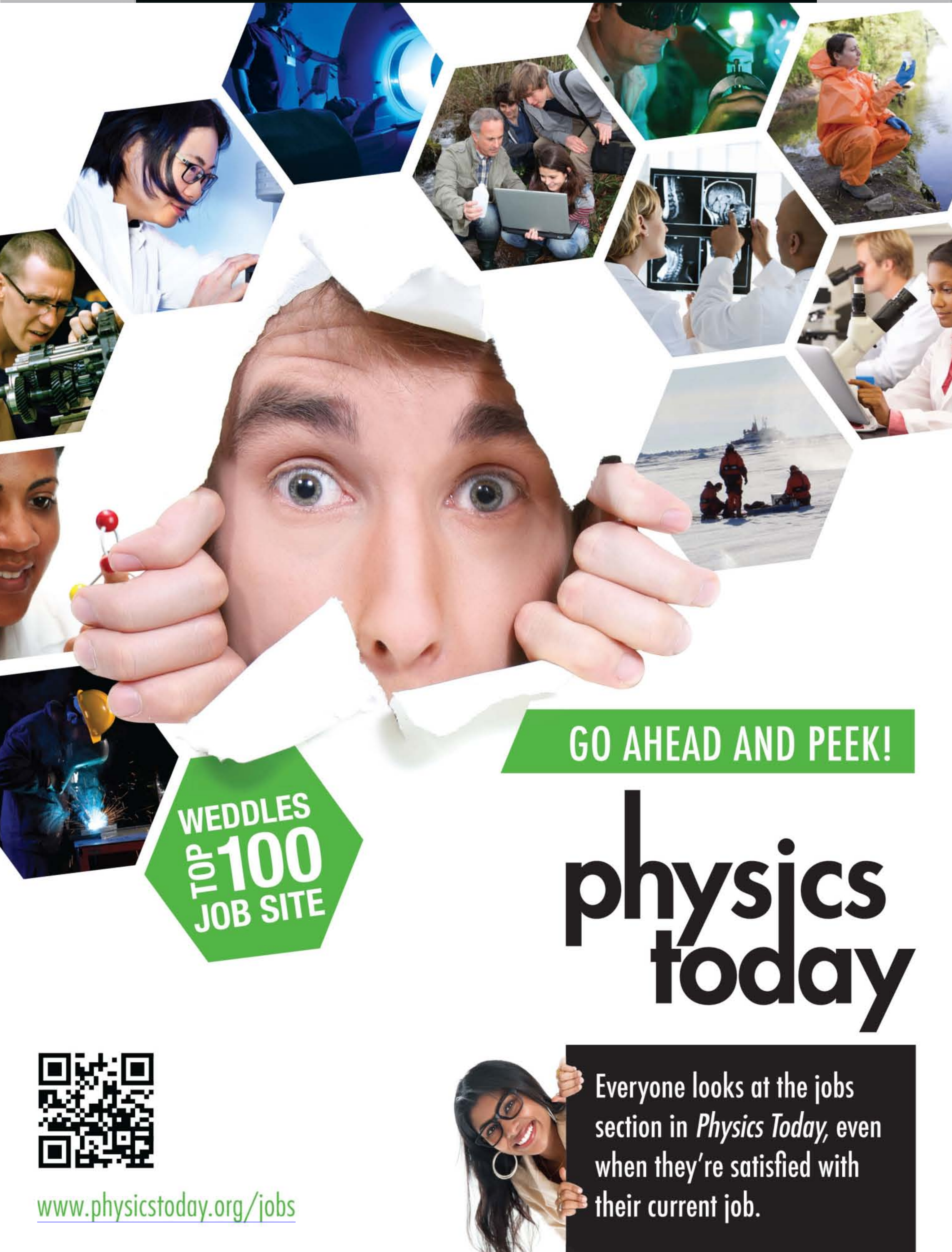
The theory also predicted a tradeoff between the increasing thrust generated when the undulation amplitude increases and the reduction of speed that ensues because the "wavelength" of the animal is thereby reduced. That tradeoff results in an optimal undulation for the most rapid swimming and the least energy consumed per unit distance moved. As shown in figure 2c, the sandfish swims almost optimally. We also tested the utility of RFT in granular media with the robot sandfish shown in figure 2d. Because of the robot's discrete construction, it can't swim as efficiently as the sandfish. But once that structure is taken into account, RFT does a good job of predicting optimal robot locomotion.

Future experimental studies, in combination with granular-media simulations, may shed more light on why RFT works well in granular media and where it fails. Potentially, such studies will also give insights about the universality of force relationships and their mechanistic basis. We have, for example, recently discovered that RFT predicts motion on the surface of granular media; that work, which involved robotic models, is briefly described in the online version of this Quick Study.

The information that scientists learn about natural locomotion should also be applicable to human-made devices operating in sandy terrain—for example, extraterrestrial rovers or robots that help at disaster sites. Those devices can certainly benefit from improved maneuverability. The Mars rovers, for example, have a top speed of 5 cm/s and occasionally suffer debilitating loss of traction.

Additional resources

▶ S. Vogel, *Life in Moving Fluids: The Physical Biology of Flow*, 2nd ed., Princeton U. Press, Princeton, NJ (1994).
▶ J. Gray, G. J. Hancock, "The propulsion of sea-urchin spermatozoa," *J. Exp. Biol.* **32**, 802 (1955).
▶ R. D. Maladen et al., "Undulatory swimming in sand: Subsurface locomotion of the sandfish lizard," *Science* **325**, 314 (2009).
▶ R. L. Hatton et al., "Geometric visualization of self-propulsion in a complex medium," *Phys. Rev. Lett.* **110**, 078101 (2013).
▶ B. Rodenborn et al., "Propulsion of microorganisms by a helical flagellum," *Proc. Natl. Acad. Sci. USA* **110**, E338 (2013).
▶ C. Li, T. Zhang, D. I. Goldman, "A terradynamics of legged locomotion on granular media," *Science* **339**, 1408 (2013). ■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academic positions

Tenure Track Assistant Professor in Physics
Oklahoma State University

The Department of Physics at Oklahoma State University seeks applicants for a new tenure-track Assistant Professor position with specialization in Medical Physics top begin Fall 2014. The new faculty hire will be expected conduct a robust research program in medical physics relevant to proton, x-ray, and electron beam therapy, to teach graduate level courses in medical physics, and to provide clinical supervision of graduate students working and training at proton and other radiotherapy centers in Oklahoma. In providing clinical supervision of students, the assistant professor will work individually with students and provide instruction and training in subject areas such as treatment planning, quality assurance, dosimetry, patient positioning, and beam delivery. The expected teaching load is 1-2 courses per semester and courses include Physics of Medical Imaging, Physics of Radiotherapy, and Radiation Protection and Dosimetry, which support our CAMPEP-accredited MS program in Medical Physics. In addition, the person appointed is expected to collaborate with current and future OSU faculty members working in radiation and medical physics in areas including the supervision of graduate student programs of study, curriculum development and student recruitment. Qualification for the position of Assistant Professor of Physics with specialization in Medical Physics is a Ph.D. in Physics or related field with considerable clinical and/or research experience in medical physics or related radiation physics areas. In addition, it is highly desirable that the individual be board certified or in the process of obtaining board certification in Medical Physics from the American Board of Radiology or the American Board of Physicists in Medicine. Applicants should submit a cover letter, a full curriculum vitae (including a full list of publications), and brief summaries of research and teaching goals, as well as arrange to have three letters of recommendation forwarded to **Chair, Search Committee, Department of Physics, Oklahoma State University, Stillwater, OK 74078-3072, USA**, or by email to: physics@okstate.edu. Applications should be received by **December 1, 2013** for full consideration. *"Oklahoma State University is an Affirmative Action/Equal Employment Opportunity employer committed to multicultural diversity. Oklahoma State University employs only U.S. citizens and lawfully authorized non-U.S. citizens. OSU participates in E-Verify to verify employment eligibility of all employees pursuant to the Oklahoma Taxpayer and Citizen Protection Act. All positions are contingent upon available funding."* C1113004

University of Maryland, Baltimore County
Faculty Position in Atmospheric Physics

The Department of Physics invites applications for a tenure-track assistant professor position in atmospheric physics to begin in August 2014. Preference will be given to candidates with specialization in any of the following areas: lidar instrumentation and remote sensing; experience with ground, airborne or laboratory measurements and modeling supporting field campaigns, satellite validation and mission development; basic atmospheric physics research in radiative transfer, light scattering or remote sensing. We seek candidates who have a demonstrated capacity to establish a vigorous, externally funded research program. A Ph.D. in Physics, Atmospheric Science or in a closely related field and the ability to teach effectively in both the graduate atmospheric physics and undergraduate physics curriculum are required. Postdoctoral experience is required and start-up funds are available. The appointment is expected to broaden and complement existing research programs in active and passive remote sensing and atmospheric modeling. Additional collaborative research opportunities exist with affiliated faculty from the UMBC/NASA GSFC Joint Center for Earth Systems Technology (http://www.jcet.umbc.edu/). In exceptional cases, the appointment may be made at a higher rank. The department currently consists of 17 tenure-track and 10 research faculty, over 45 graduate students and 150 majors. The department offers a BS in Physics, and both MS and Ph.D. degrees in Atmospheric Physics and in Applied Physics. Research expenditures currently exceed $5M per year. (For more information see: http://physics.umbc.edu). Please submit an application letter, a resume, research and teaching plans and the names and addresses of at least three references to **Chair of the Search Committee, Department of Physics, UMBC, 1000 Hilltop Circle, Baltimore MD 21250,** Email: Physics@umbc.edu. The selection process will begin **November 15, 2013** and will continue until the position is filled. *The department is especially interested in candidates who can contribute to the diversity and excellence of the academic community through research, teaching and service. UMBC is an Affirmative Action/Equal Opportunity Employer.* C1113005

Tenure-Track Faculty Position in Condensed Matter Physics
University of Washington, Department of Physics

Outstanding candidates in condensed matter experiment or theory are invited to apply for a full-time tenure-track appointment, at any rank, in the Department of Physics at the University of Washington in association with the new Clean Energy Institute (http://cei.washington.edu/). Of particular interest is research with possible energy related applications (such as electrochemical energy storage or photo-voltaics). University of Washington faculty members engage in teaching, research, and service. The successful applicant will be expected to participate in undergraduate and graduate teaching and to develop an innovative, vigorous, externally-funded research program. Applicants must have a Ph.D. or foreign equivalent degree by the date of appointment. Applications must be submitted at https://academicjobsonline.org/ajo/jobs/3188, and should include a cover letter, curriculum vitae, statement of future research interests and, at the Assistant Professor rank, three letters of reference. Review of applications will begin on **October 28, 2013**. Please direct all inquiries to facsrch@uw.edu. *The University of Washington is an affirmative action, equal opportunity employer. The University is building a culturally diverse faculty and strongly encourages applications from female and minority candidates.* 1947901

University of San Diego

www.sandiego.edu

Tenure-Track Assistant Professor-Physics

The Department of Physics at the University of San Diego (www.sandiego.edu/cas/physics), an independent Catholic university, invites applications for a tenure-track assistant professor of physics position expected to begin September 2014. Applicants are expected to have a doctorate in Physics, a passion for physics undergraduate education, and a desire to pursue research suitable for undergraduates in the field of biophysics and/or related fields. The Department, housed in a modern 150,000 sq. ft. interdisciplinary science facility, strives to maintain a personalized, student-centered approach to teaching and a collaborative approach to productive undergraduate research. The successful candidate will be expected to teach undergraduate lower and upper division lecture and laboratory courses including specialized biophysics courses in his/her field of expertise, and to participate in the development of physics programs, especially the biophysics program (new as of Fall 2011). The department is strongly committed to diversity and especially encourages applications from ethnic minorities and members of other underrepresented groups. To submit application materials (vita, statements on teaching and research), go to **http://apptrkr.com/396912** and reference Job IRC11987. Further, three letters of recommendation should be e-mailed to the Department of Physics Executive Assistant, Kathy Andrews, at andrewsk@sandiego.edu, Subject: SearchPhysics2014. Application materials will be reviewed starting January 3, 2014 and continuing until the position is filled.

USD is an Equal Opportunity Employer

Assistant Professor of Physics and Astronomy
University of Wisconsin - Stevens Point

Applications are invited for a tenure-track faculty position to begin in fall 2014. The successful candidate will be expected to: i) teach all levels of undergraduate physics and introductory astronomy, ii) involve students in substantial undergraduate research activities, preferably in atomic, molecular, and optical physics, and iii) serve the Department and the University through student advising, participation in shared governance, and outreach. Ph.D. in physics or closely related area is required (A.B.D. candidates will be considered). Teaching experience is desirable. We strongly encourage applications from persons with diverse backgrounds and experiences. Appointment is expected at the assistant professor level. Salary will be commensurate with qualifications and experience. Please provide a letter of application, resume, photocopies of undergraduate and graduate transcripts (official transcripts will be required prior to the time of hire), a statement of teaching philosophy, and a statement of research plans including startup costs. Also arrange for three current letters of reference to be sent to **Dr. Mick Veum, Chair, Department of Physics and Astronomy, University of Wisconsin – Stevens Point, Stevens Point, WI 54481.** Review of applications will begin on **December 1, 2013**. For full position announcement, please visit our website http://www.uwsp.edu/equity/Job%20Vacancies/14-53F03.pdf. *The University of Wisconsin – Stevens Point is an EEO/AA employer. Employment will require a criminal background check.* 1948087

Laboratory of Chemical Physics, NIDDK, National Institutes of Health
Postdoctoral Positions
Computational Biophysics

Post-doctoral research positions in computational biophysics are available in the Laboratory of Chemical Physics, NIDDK, NIH: http://www2.niddk.nih.gov/NIDDKLabs/AllLabs/Laboratories/LaboratoryofChemicalPhysics.htm. The Laboratory is located on the main intramural campus of the NIH in Bethesda, Maryland, just outside Washington, D.C., and the research of all groups is primarily concerned with problems in the structure, dynamics, and function of biological macromolecules. The positions will be in the research group of Dr Robert Best, where areas of particular interest include protein folding dynamics and mechanism, but also the development of new simulation methodology and techniques. The ideal candidate would have a background in statistical mechanics, molecular simulation or related area. Interested applicants should send a CV and list of publications to **Dr Robert Best** at robertbe@helix.nih.gov and arrange for three academic references to be sent directly by email. C1113015

Tenure track faculty position in Cosmology
Virginia Tech

The College of Science at Virginia Tech, in support of the university's strategic plan, is expanding its research presence in: Energy and the Environment, Infectious Diseases, Nanoscience, Neuroscience, Computation and Visualization & Pattern Recognition. As part of this initiative, the Department of Physics has a tenure-track opening in cosmology, broadly defined, including all areas of theoretical, observational, experimental, and computational cosmology, to start in the fall of 2014 at its Blacksburg, VA campus. Appointment at the assistant professor level is anticipated but exceptional senior candidates will be considered. The department has existing research areas in galaxy formation and evolution, early universe cosmology, string theory and particle physics represented by the Center for Neutrino Physics. Candidates who will complement and extend at least one of these research areas are particularly encouraged to apply. Applicants must have a Ph.D. in physics, astronomy or a closely related field, postdoctoral experience, and pass a criminal background check. The successful candidates will be expected to establish a vigorous research program, teach effectively at the undergraduate and graduate levels, continue development of scholarly activities and professional capabilities, and participate in department, college, and university governance. Occasional travel to attend professional conferences is required. The faculty handbook (available at http://www.provost.vt.edu) gives a complete description of faculty responsibilities. Questions regarding the position can be directed to **Prof. Patrick Huber, Chair, Cosmology Search, Physics Department, Robeson Hall, Virginia Tech, Blacksburg, VA 24061, Tel: (540) 231-8727,** Email: cosmology@phys.vt.edu. Applications must be submitted online at http://listings.jobs.vt.edu (posting **TR0130071**). The application package should include a cover letter, curriculum vitae, a research plan and a statement of teaching philosophy. Applicants should arrange for at least three letters of recommendation to be submitted directly to the Search Chair. Review of applications will begin on **January 6, 2014**. *Virginia Tech is an EO/AA university, and offers a wide range of networking and development opportunities to women and minorities in science and engineering. The physics department offers a supportive environment, including a mentoring program, to its junior faculty. Individuals with disabilities desiring accommodations in the application process should notify Mrs. Sue Teel, Physics Department, (540) 231-7566, or call TTY 1-800-828-1120.* 1948529

Tenure Track Position – Experimental Physics
Cornell University

The Laboratory of Atomic and Solid State Physics (LASSP) at Cornell University expects to make a faculty appointment in experimental physics, to begin July 1, 2014. We encourage applications in cold atom physics, biophysics, hard and soft condensed matter physics, x-ray physics, and related areas that utilize condensed matter tools and techniques. The search will focus at the assistant professor level, although more senior candidates may be considered. The successful candidate will be expected to conduct an outstanding independent research program and be an effective teacher in the undergraduate and graduate instructional program of the Physics Department. Please send the application, including a curriculum vitae, a publication list, and a statement of research and teaching interests, to https://academicjobsonline.org/ajo/jobs/3262. Applicants should arrange to have three letters of reference sent to the same website. Applications completed by **Dec. 15, 2013** will receive full consideration. *Cornell University is an Affirmative Action, Equal Opportunity Employer and Educator.* C1113006

Assistant Professor in Quantitative Biology
University of California, San Diego

The Division of Physical Sciences at the University of California, San Diego, is pleased to invite applications from outstanding candidates for a tenure-track faculty position in the area of Quantitative Biology. The emphasis is on candidates that address issues in living systems with a broad set of experimental skills, including the possibility of instrument and probe development, as well as analytical skills. Candidates with a focus on network interactions - from genes through cell-to-cell communication - are particularly encouraged to apply. This position is at the level of Assistant Professor and is part of a campus-wide thrust toward quantitative approaches in the study of living systems. Departmental affiliation will be tailored to the selected candidate and, in keeping with the highly interdisciplinary nature of the research community at UCSD, the successful candidate may affiliate with other academic divisions across campus. All candidates must have earned a Ph.D. or equivalent degree. The University is committed to academic excellence and diversity within the faculty, staff, and student body. Preference in hiring will be given to candidates with demonstrated creativity and scholarship in their research, a passion for teaching at the undergraduate and graduate levels, and demonstrated potential for leadership in areas contributing to diversity, equity, and inclusion. Salary will be commensurate with qualifications and based on University of California pay scales. Review of applications will commence on **November 4, 2013** and will continue until the position is filled. Applicants must submit a cover letter, a curriculum vitae with a list of publications, a research plan, a statement of past and proposed teaching, reprints of three representative publications, contact information for three to five references, and a separate statement on past experience and leadership in equity, diversity, and inclusion and/or proposed future contributions (see http://facultyequity.ucsd.edu/Faculty-Applicant-C2D-Info.asp.) Applications must be submitted online at https://apol-recruit.ucsd.edu/apply/JPF00438. *UCSD is an Affirmative Action/Equal Opportunity Employer with a strong institutional commitment to excellence through diversity.* 19479319

Assistant, Associate or Full Professor
University of Minnesota

Tenured or Tenure-Track Faculty Position, Chemical Engineering and Materials Science, University of Minnesota. The Department of Chemical Engineering and Materials Science at the **University of Minnesota** (http://www.cems.umn.edu/) seeks to fill a faculty position at the Assistant (tenure-track), Associate, or full Professor level, commensurate with experience. Outstanding candidates with a PhD degree in any area related to chemical engineering and materials science will be considered. Candidates should have a distinguished academic and research record and a commitment to teaching in a highly interdisciplinary department. Applications, consisting of a CV (including a list of publications), a research plan, a teaching plan, and a list of three references with contact information (including email addresses), should be submitted online at https://employment.umn.edu. Search for requisition number **186204**. Review of applications will begin immediately and continue until the position is filled. The successful candidate will be in place as early as Fall 2014. *The University of Minnesota is an equal opportunity educator and employer.* C1113018

Tenure Track Faculty Position in Nanophysics
Georgia State University

The Department of Physics and Astronomy at Georgia State University invites applications for a tenure-track, Assistant Professor position in the areas of experimental nanomaterials, metamaterials, nanophotonics/nanoplasmonics, ultrafast spectroscopy, spectroscopic imaging of nanosystems, or nanosensors for nuclear physics, to begin in August 2014. The successful candidate will be expected to teach and establish a vigorous, funded research program that complement and enhance existing research in any of the above listed areas in the department. Candidates must hold a PhD in Physics, Applied Physics, Chemical Physics, or Electrical Engineering, and must have at least three years of relevant post-doctoral experimental research experience in any of the aforementioned areas. The department seeks candidates who have demonstrated excellence in scholarly research and can develop independent but complementary research directions, as well as contribute to educational programs. To apply, submit an application letter, a CV with a publication list, a detailed research plan explaining how the proposed research complement and enhance existing research, teaching plans, and the names and addresses of at least three selected references to Nanophysics Search Committee at PhySearch@phy-astr.gsu.edu. Application materials should be in PDF format. Questions about the position can be directed to uperera@phy-astr.gsu.edu. In order to receive full consideration, applications should be received by **Dec 9, 2013**. The position will remain open until filled. An offer of employment will be conditional on background verification. *Georgia State University, a unit of the University System of Georgia, is an equal opportunity educational institution, and an EEO/AA employer.* 1934172

Faculty Position in Theoretical Cold Atom Physics
Rice University

The Department of Physics and Astronomy at Rice University invites applications for a tenure-track Assistant Professor position in theoretical physics. Applicants are expected to have expertise in ultra-cold atom physics, with a focus on connections to condensed matter physics. This position will complement and extend our existing experimental and theoretical strength in both ultra-cold atom and condensed matter physics (for information on the existing efforts, see http://physics.rice.edu/). A PhD in physics or related field is required. Applicants should send a dossier that includes a curriculum vitae, statements of research and teaching interests, a list of publications, and two or three selected reprints, in a single PDF file to **vcall@rice.edu** or to **R. G. Hulet** or **Han Pu, Co-Chairs, Faculty Search Committee, Dept. of Physics and Astronomy – MS 61, Rice University, 6100 Main Street, Houston, TX 77005.** Applicants should also arrange for at least three letters of recommendation to be sent by email or post. Applications will be accepted until the position is filled, but only those received by **November 30, 2013** will be assured full consideration. The appointment is expected to start in July, 2014. *Rice University is an affirmative action/equal opportunity employer; women and underrepresented minorities are strongly encouraged to apply.* C1113022

北京大学 北京大学定量生物学中心 CENTER FOR QUANTITATIVE BIOLOGY

Faculty and Postdoctoral Positions at the Center for Quantitative Biology

The Center for Quantitative Biology (CQB) at **Peking University (PKU)** invites application for faculty positions at all ranks. We seek for creative individuals in all areas of quantitative biology, with emphases on (but not limited to): (1) Systems biology; (2) Synthetic biology; (3) Computational biology/Bioinformatics; (4) Disease mechanism and drug design from system biology perspective; (5) Development of quantitative methods and technology. As part of PKU's strategic initiative in enhancing interdisciplinary research, CQB is dedicated to research and education at the interface between the traditionally more quantitative disciplines (such as mathematics, physical sciences, engineering, computer science) and the biological sciences. Current research areas include: systems biology, synthetic biology, bioinformatics, computational biology, and network based disease mechanism and drug design. Faculty at CQB can also be associated with other schools and departments at Peking University and have the opportunity to join the Peking -Tsinghua Center for Life Sciences. We offer an internationally competitive start-up package and an excellent interdisciplinary research environment with outstanding core research facilities.

CQB also seeks individuals with strong quantitative background for postdoctoral positions. Applicants should have received a Ph.D. degree within five years. We offer a competitive postdoc stipend up to ¥200,000 per year.

Application should include a CV, a research plan, names of three references, a publication list, and 3 representative publications, and be submitted to: gongsy@pku.edu.cn.

USC University of Southern California

The Department of Aerospace and Mechanical Engineering at the University of Southern California is seeking applications and nominations for the position of Department Chair. The candidate must have an outstanding record of scholarly and technical achievements, a strong commitment to engineering education, effective management and interpersonal skills, and must be eligible for appointment at the full professor level. Exceptionally strong candidates will also be considered for appointment to an endowed professorship. A PhD degree in aerospace or mechanical engineering or a related field is required. Applications should be received preferably by **December 2, 2013**. Information about the department can be found at **http://ame-www.usc.edu**.

Interested candidates should prepare an application package consisting of their personal contact information; a curriculum vitae; a cover letter describing their technical qualifications, thought on leadership, and their vision of the field in the future; and contact information for at least four professional references. All material in the application package is to be submitted electronically at **http://ame-usc.edu/facultypositions/**.

Inquiries should be directed to the **Search Committee Chair, Prof. Lucio Soibelman** at **soibelman@usc.edu**.

USC is an equal-opportunity/affirmative action employer. Women and underrepresented minorities are especially encouraged to apply.

Tenure Track Assistant Professor
Williams College

The Physics Department invites applications from experimentalists for an Assistant Professor position with teaching duties starting 9/14. A more senior appointment is possible in exceptional circumstances. Ph.D. required; postdoctoral research experience preferred. We seek an energetic individual eager to teach throughout the undergraduate curriculum and to involve undergraduates in experimental physics research. Startup funds will be available. Williams is a highly selective, private, coeducational, liberal arts college. For the current faculty and the postgraduate plans of recent majors see physics.williams.edu. The College is working to increase the ethnic and gender diversity of its science majors and seeks individuals who can help us meet those goals. Applications should be submitted via https://secure.interfolio.com/apply/22001 and include a c.v., a statement of research plans, a statement of teaching interests and two (or more) letters of reference. Those completed by **Nov. 15** will receive full consideration. **Kevin Jones, Department Chair,** PhysicsChair@williams.edu. *Beyond meeting fully its legal obligations for non-discrimination, Williams is committed to building a diverse and inclusive community where members from all backgrounds can live, learn, and thrive. All offers of employment are contingent upon completion of a background check, see dean-faculty.williams.edu/prospective-faculty/background-check-policy.* 1927720

Tenure-Track Position in Applied Physics
Cornell University

Cornell is a community of scholars, known for intellectual rigor and engaged in deep and broad research, teaching tomorrow's thought leaders to think otherwise, care for others, and create and disseminate knowledge with a public purpose.

The School of Applied and Engineering Physics at Cornell University is seeking applications for a tenure-track, assistant professor position. Consideration of applications for an associate or full professor level position may be given to exceptionally well-qualified individuals. Candidates must be able to demonstrate the ability to develop a highly successful independent research program and to participate effectively in the teaching of the applied physics curriculum at both the undergraduate and graduate levels. Research areas of interest include biophysics and biotechnology, optics and photonics, nanostructure science and technology, novel instrumentation methods, computational physics, renewable energy, and materials physics. However, exceptional candidates in all areas of applied physics will be given serious consideration. Prospective candidates who wish to pursue interdisciplinary research efforts are strongly encouraged to apply. The successful applicant can expect a highly competitive level of support for the start-up of his/her research program. Considerable institutional resources are available at Cornell that can strengthen this research program and support interdisciplinary and collaborative research ventures. The successful candidate can expect to benefit from association with one or more of Cornell's interdisciplinary research centers, national facilities, and national resources, listed at **http://www.engineering.cornell.edu/research/facilities.cfm**. Interested applicants should go to the following link to submit their curriculum vitae, a statement of teaching philosophy, a brief (3-page limit) statement of research interests, and the names and complete contact information for at least three references: **https://academicjobsonline.org/ajo/jobs/3097**. An automated message will be sent to all references requesting letters. Applications will be accepted until December 22, 2013.

The School of Applied and Engineering Physics and the College of Engineering at Cornell embrace diversity and seek candidates who will create a climate that attracts students of all races, nationalities, and genders. Cornell University is an affirmative action/equal opportunity employer; qualified women and minority candidates are particularly encouraged to apply.

Cornell University seeks to meet the needs of dual career couples, has a Dual Career program, and is a member of the Upstate New York Higher Education Recruitment Consortium to assist with dual career searches. Visit **http://www.unyherc.org** to see positions available in higher education in the upstate New York area.

Find us online at http://hr.cornell.edu/jobs or
Facebook.com/CornellCareers

Cornell University is an innovative Ivy League university and a great place to work. Our inclusive community of scholars, students and staff impart an uncommon sense of larger purpose and contribute creative ideas to further the university's mission of teaching, discovery and engagement. Located in Ithaca, NY, Cornell's far-flung global presence includes the medical college's campuses on the Upper East Side of Manhattan and in Doha, Qatar, as well as the new CornellNYC Tech campus to be built on Roosevelt Island in the heart of New York City.

Diversity and inclusion have been and continue to be a part of our heritage.
Cornell University is a recognized EEO/AA employer and educator.

Assistant, Associate or Full Professor of Astronomy
Physics Department

Amherst College's Department of Physics invites applications for a full-time tenure-track or tenured appointment in astronomy that will begin in July 2014. The College seeks an individual who will bring energy and enthusiasm to Amherst's storied astronomy program as a part of a new Department of Physics and Astronomy. The successful candidate will have broad intellectual interests and be committed to teaching and establishing an active research program involving undergraduates. He or she will also be a member of the Five College Astronomy Department, a collaborative program of Amherst, Smith, Mount Holyoke, and Hampshire Colleges and the University of Massachusetts. *Amherst College is an equal opportunity employer and encourages women, persons of color, and persons with disabilities to apply. The College is committed to enriching its educational experience through the diversity of its faculty, administration, and staff.* This is an open-rank search. An appointment at the assistant, or, possibly, the associate professor rank, will be tenure track. A senior appointment would be with tenure. Any appointment with tenure will be contingent upon tenure review. A Ph.D. in astronomy, astrophysics, or a closely related field is required; preference will be given to candidates with postdoctoral research and teaching experience. Start-up funds are available. Applicants should submit a letter of application, current curriculum vitae, including a list of publications, and a letter describing plans for teaching and research. Application materials should be submitted electronically at https://jobs.amherst.edu/view/opportunity/id/585. In addition, applicants should arrange to have three letters of recommendation sent to **Professor David Hall, Chair, Department of Physics, AC #2244, Amherst College, Amherst, MA 01002-5000,** or by e-mail to physicschair@amherst.edu. Review of applications will begin on **November 15, 2013**, and continue until the position is filled. Amherst is a private undergraduate liberal arts college for men and women, with 1,800 students and a teaching faculty of more than two hundred. More information about the College can be found at www.amherst.edu. C1113012

Tenure Track Assistant/Associate Professor
Department of Physics/University of Miami

The Department of Physics at the University of Miami invites applications from highly qualified persons for a tenure–track position in Condensed Matter Physics at the Assistant or Associate Professor rank to begin Fall 2014. Experimental candidates are particularly encouraged to apply. Current departmental research in this area involves electronic, magnetic, thermal and superconductive properties of novel materials with potential device applications. Candidates must have a Ph.D. in physics or related field, a demonstrated record of research achievements, and a strong commitment to teaching and mentoring students at the undergraduate and graduate levels. The physics department is located within the University's attractive Coral Gables campus in the greater Miami area, and has a wide-ranging research expertise and established Ph.D. program. Application materials, including curriculum vitae with list of publications and statement of research plans, should be sent electronically (as a single PDF) to barnes@physics.miami.edu or to **Prof. Stewart E. Barnes, CM Search Committee Chair, Department of Physics, University of Miami, Knight Physics Building, Coral Gables, Fl. 33124.** Applicants should arrange for three letters of recommendation to be sent to the same address. Review of applications will begin on **November 18, 2013** and continue until the position is filled. *The University of Miami is an equal opportunity/affirmative action employer that values diversity and has progressive work-life policies. Women, persons with disabilities, and members of other underrepresented groups are encouraged to apply.* 1928683

Hybrid Quantum Devices
The Institute for Quantum Computing

Applications are invited for PhD, Postdoctoral fellows and Research Associate positions in Professor Cory's laboratory at the Institute for Quantum Computing, **University of Waterloo**. Projects involve the design, fabrication and testing of solid-state, spin-based qubits with applications to small quantum processors. In particular we are interested in hybrid devices that couple nuclear and electron spins with superconducting electronics. Some devices also include transport and optical detection. The laboratory is very well equipped for NMR, ESR, deposition and growth and low-temperature physics. Start date and length of appointment are open. Please send a CV to **Professor Cory** (dcory@uwaterloo.ca). 1939563

University at Buffalo
The State University of New York
Faculty Position in Theoretical Particle Physics

The Department of Physics of the University at Buffalo (UB), The State University of New York, invites applications for a tenure-track assistant professor position in theoretical particle physics to begin in the fall of 2014. We seek candidates with a strong background in collider phenomenology, who will complement and strengthen the current research efforts of the High-energy Physics and Cosmology group (HEPCOS) at UB. Faculty in the Physics Department are expected to maintain an excellent and well-funded research program, contribute to departmental teaching at the Undergraduate and Graduate levels, advise and mentor graduate students and provide service to the department, university, and community at large. Candidates for this position are required to have a Ph.D. and postdoctoral experience in theoretical particle physics. For full consideration, all application materials must be received by **December 1, 2013**. The application must include a cover letter, separate research and teaching statements, describing current and planned research and teaching activities, and a curriculum vita including a list of publications. Applicants should arrange for at least three letters of reference. Applications and reference letters must be submitted online at https://www.ubjobs.buffalo.edu/applicants/Central?quickFind=56488. Only electronic submissions of applications will be considered. Informal inquiries can be sent to the **Search Committee Chair, Professor Doreen Wackeroth**, dw24@buffalo.edu. Members of the HEPCOS group conduct research in theoretical and experimental high-energy physics and cosmology. UB is a member of the Tevatron D0 and LHC CMS collaborations and high-energy theorists in the group enjoy close collaborations with their experimental colleagues. For more information about the HEPCOS group please visit www.physics.buffalo.edu/hepcos. *SUNY at Buffalo is an Affirmative Action/Equal Opportunity employer committed to diversity and inclusion.* C1113024

PhD Scholarships
Max Planck Institute for Nuclear Physics (MPIK)

The International Max Planck Research School for Quantum Dynamics in Physics, Chemistry and Biology (IMPRS-QD) is a graduate school offering a doctoral degree program in these disciplines. The IMPRS-QD is a joint initiative of the Max Planck Institute for Nuclear Physics (MPIK), the Heidelberg University, the German Cancer Research Center (DKFZ), the Max Planck Institute for Medical Research (all in Heidelberg) and the Heavy Ion Research Center (GSI) in Darmstadt. Applications of students from all countries are welcome. To be eligible for PhD studies at the Heidelberg University, applicants should have an excellent Master of Science degree (or equivalent). International applicants whose mother-tongue is not English or German have to provide a proof of English proficiency. Interested students are asked to apply via web form at: http://www.mpi-hd.mpg.de/imprs-qd/appladmiss.html. The application deadline is 1 **December 2013**. 1917450

Assistant or Associate Professor of Applied Mathematics
Columbia University, Fu Foundation School of Engineering

Department of Applied Physics and Applied Mathematics, Open-rank Faculty Position in Applied Mathematics. Columbia Engineering's Department of Applied Physics and Applied Mathematics (APAM) at Columbia University in New York City invites applications for tenure-track faculty positions. Appointments at the assistant professor or associate professor will be considered. Applications are specifically sought in any of the areas that fall under the umbrella of the Applied Mathematics Program within APAM, with particular emphasis on, but not limited to Applied and Computational Mathematics and its applications in many areas of Applied and Engineering Physics, Earth and Environmental Sciences, and Biological Sciences. Candidates must have a Ph.D. or its professional equivalent in Applied Mathematics or a related field by the starting date of the appointment. Applicants for this position at the Assistant Professor and Associate Professors without tenure must have the potential to do pioneering research and to teach effectively. The successful candidate should contribute to the advancement of the department in these areas by developing an externally funded research program, contributing to the undergraduate and graduate educational mission of the Department and is expected to establish multidisciplinary research and educational collaborations with academic departments and units across Columbia University. The Department is especially interested in qualified candidates who can contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community. Candidates should apply online at: academicjobs.columbia.edu/applicants/Central?quickFind=58252 and should submit electronically the following: curriculum-vitae including a publication list, a description of research accomplishments, a statement of research/teaching interests and plans, contact information for three people who can provide letters of recommendation, and up to three pre/reprints of scholarly work. The position will close no sooner than **November 20, 2013** and will remain open until filled. Applicants can consult http://www.apam.columbia.edu for more information about the department. *Columbia is an affirmative action/equal opportunity employer with a strong commitment to the quality of faculty life.* 1949520

Faculty Position in School of Physical Science and Technology (SPST)

ShanghaiTech University (http://www.shanghaitech.edu.cn/index.asp) is a newly established Research University (RU/VH) located at Zhang-Jiang High-Tech Park in Pudong, Shanghai, China. Currently, it has four schools; School of Physical Science and Technology, School of Life Science and Technology, School of Information and Technology and School of Entrepreneurial and Management with expected enrollment of 4,000 graduate and 2,000 undergraduate students. The new University is jointly supported by Chinese Academy of Science (Shanghai Branch) and Shanghai Municipal Government. The vision of ShanghaiTech is to be a globally recognized top research university for its size and profound integration of education, research and innovation by creating a dynamic people centered hub where innovative research, education, and community service meet to provide a multi-disciplinary approach to learning and to solving problems facing society. As a new university, we have successfully recruited over 20 real high caliber tenure-track faculties so far. We expect to set up new policies to support an academic environment for best practices of research, teaching and learning. The University will build state of art research and teaching facilities including large research instruments, modern library and classrooms. Shared governance will be a part of the campus culture. School of Physical Science and Technology (SPST) is expected to have about 100 regular tenured and tenure-track faculty, 1,200 graduate and 750 undergraduate students. The School is established to encourage interdisciplinary research particularly focused on Materials, Environment and Energy. We are currently seeking applicants for multiple tenure-track and tenured positions at all ranks. **Qualifications:** Successful applicants should have a doctoral degree in Physical Science and Engineering as well as postdoctoral experience for junior level position. They will be expected to establish an independent, internationally recognized research program. Supervise students and teach two course a year. The senior position applicants are expected be leading scientists in his/her research disciplinary. We particularly welcome those with research interests related to Energy, Materials and Environment Science and Engineering to apply. **Initial Research Support Package:** University will provide an average of $320K initial start-up fund plus a partial support of a Research Associate and Post-Doctor. Research lab space will be provided matching the research needs. Our faculty will have the access to the research facilities and resources of Chinese Academy of Science. Compensation and Benefits:Starting salary will be competitive and commensurate with qualifications and experience. We offer a comprehensive benefits package including health and retirement benefits as well as on campus housing renting at a reduced rate. University will also sponsor applications of national and local Talent Programs based on individuals' qualification and experience. **Application Procedure:** Applications should include curriculum vitae, a 2-3 page statement of research interests and the names and addresses of three individuals who can serve as references for the candidate. These materials should be sent to **Mrs. Zhou Qing, School of Physical Science and Technology, ShanghaiTech University, Building 8, 319 Yueyang Road, Shanghai 200031, China.** Electronic submissions are strongly encouraged (email:SPST@shanghaitech.edu.cn). Review of applications will continue until positions filled. C1113021

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Faculty Position in Multi-scale Manufacturing Technologies

at the Ecole polytechnique fédérale de Lausanne (EPFL)

The Institute of Microengineering (IMT) within the School of Engineering at EPFL invites applications for a faculty position at the level of tenured professor or tenure track assistant professor in **multi-scale manufacturing technologies** for its Neuchâtel site. This new position is aimed at reinforcing the leading position of the Swiss microengineering industry by giving it the means to further strengthen its competitiveness by continuous innovation.

Specific areas include, but are not limited to:

- **high-precision additive manufacturing technologies;**
- **multi-scale micro-precision** manufacturing;
- **high throughput** manufacturing;
- manufacturing of **complex 3D** mechanical components;
- **advanced manufacturing processes** compatible with standard materials used for micro-mechanics in watchmaking and other applications.

Experience in successful collaborative research programs with industry is highly desirable. The Neuchâtel site of IMT-EPFL offers a particularly advantageous position for this chair due to its central location in the Jura Arc, which is the home to many of the key watchmaking companies, and to its historically very strong links to the diverse and well-established local high-technology industry.

As a faculty member of the School of Engineering, the successful candidate is expected to initiate an independent, creative research program, participate in undergraduate and graduate teaching and establish strong links with industrial partners. Internationally competitive salaries, start-up resources and benefits are offered.

Applications should include a cover letter with a statement of motivation, curriculum vitae, list of publications and patents, concise statement of research and teaching interests, and the names and addresses of 5 references. Applications must be uploaded in PDF format to the web site: **manufacturing.epfl.ch**

Formal evaluation of candidates will begin on **15 December 2013** and continue until the position is filled.

Enquiries may be addressed to:
Prof. Christian Enz
Search Committee Chair
E-mail: **manufacturing-search@epfl.ch**

For additional information on EPFL, please consult the web sites **www.epfl.ch**, **sti.epfl.ch** and **imt.epfl.ch**.

EPFL is committed to increasing the diversity of its faculty, and strongly encourages women to apply.

USC University of Southern California

The Department of Aerospace and Mechanical Engineering at USC is seeking applications and nominations for tenure-track or tenured faculty in the area of thermo-fluids. Though we particularly encourage applications in the fields of combustion and fluid mechanics, consideration will be given to a broad spectrum of outstanding candidates. We also encourage special applications from more senior scholars who have a well-established academic record and whose accomplishments are leading/transforming their fields of study. Exceptionally strong candidates will also be considered for appointment to an endowed professorship.

Applicants must have earned a Ph.D. or the equivalent in a relevant field by the beginning of the appointment and have a strong research and publication record. Applications must include a letter clearly indicating area(s) of specialization, a detailed curriculum vitae, a concise statement of current and future research directions, a teaching statement, and contact information for at least four professional references. This material should be submitted electronically at **http://ame-www.usc.edu/facultypositions/**. Early submission is strongly advised and encouraged as the application review process will commence **January 6, 2014**.

USC Viterbi
School of Engineering

The University of Southern California values diversity and is committed to equal opportunity inemployment. Men, women and members of all racial and ethnic groups are encouraged to apply.

北京大学

Faculty and Postdoctoral Positions

INTERNATIONAL CENTER FOR QUANTUM MATERIALS
PEKING UNIVERSITY, CHINA

The International Center for Quantum Materials (ICQM, http://icqm.pku.edu.cn/), Peking University, China, invites applications for tenured/tenure-track faculty positions and postdoctoral positions in the fields of experimental and theoretical condensed matter physics, material physics, and related areas. ICQM is dedicated to bringing in both internationally-renowned scientists and excellent young researchers from different areas of condensed matter and material physics and enabling them to work together productively. The center has 10 permanent positions (tenured and tenure-track faculty members) and an unlimited number of postdoctoral positions open for applications.

Positions and Qualifications
We are seeking exceptional candidates for all levels of faculty positions, including distinguished chair professors, tenured full/associate professors, as well as tenure-track associate/assistant professors. Candidates should have a Ph.D. in a relevant discipline, an outstanding record of research accomplishments, and the capability to lead an independent research group. The individual's work experience and research performance will determine the position offered. In particular, candidates applying for position of distinguished chair are expected to be internationally influential in a relevant discipline.

We are also seeking qualified candidates for postdoctoral positions. Candidates should have a Ph.D. in a relevant discipline or expect a Ph.D. within a year, with a substantive record of research accomplishments, and the ability to work collaboratively with faculty members in the Center. The research directions and informations of prospective advisors can be found in our website.

Salary and Benefits
All newly hired faculty members will be provided the necessary startup resource and research infrastructures. Annual salaries for regular positions range from 250K to 550K RMB (equivalent to US$38,500-85,000). Salaries for distinguished chair professors are internationally competitive and are to be separately negotiated in each case.

Postdoctoral fellows will be provided an annual stipend up to 200K RMB (equivalent to US $30,000), based on individual's experience and research performance. Housing subsidies will also be provided.

To Apply: Applicants should send a full curriculum vitae; copies of 3-5 key publications; three letters of recommendation; and a statement of research (for permanent position applicants only) to, **Professor Qian Niu at ICQM@pku.edu.cn**

Application for a postdoctoral position can also be directly addressed to an individual prospective advisor.

physicstoday Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page physicstoday

Assistant Professor
Emory University

Faculty Position in Condensed Matter Physics at Emory University The Department of Physics at Emory University invites applications for a tenure-track faculty position at the assistant professor level in experimental or theoretical Condensed Matter Physics, to begin in September 2014. This is one of multiple positions planned as part of the strategic expansion of Materials Physics research at Emory University. We are particularly interested in applicants who will benefit from and complement the existing strengths in nanoscience, photonics, spintronics, energy materials, statistical, nonlinear, and computational condensed matter physics. For a detailed description of ongoing departmental research, see http://www.physics.emory.edu/research.html. Applicants must have a PhD in physics or a closely related field, and a proven record of research accomplishment. The successful candidate will be expected to establish an independent, internationally recognized and externally funded research program, and demonstrate excellence in teaching at both undergraduate and graduate levels. The successful applicant will have access to the state-of-the art materials research and nanofabrication facilities maintained by the Department of Physics and other research support centers at Emory, as described at http://www.physics.emory.edu/Facilities/. To apply, submit a curriculum vitae, a research plan, and a teaching statement to search2013@physics.emory.edu. Applicants should arrange for at least three letters of recommendation to be sent to the same address. Review of applications will begin **November 1, 2013** and will continue until the position is filled. *Emory University is an Affirmative Action/Equal Opportunity employer. Women and members of underrepresented groups are particularly encouraged to apply.* 1922912

BROWN UNIVERSITY
FACULTY POSITION
IN
EXPERIMENTAL CONDENSED MATTER PHYSICS

The Department of Physics at Brown University invites applications for a tenure- track Assistant Professor position in Experimental Condensed Matter Physics, starting in the summer of 2014. This position is part of an initiative for further growth in interdisciplinary science at Brown University, including the recent establishment of the School of Engineering. We seek candidates who have the potential to create a vigorous and sustainable research program at Brown. A strong commitment to teaching at the undergraduate and graduate levels is also required. Current research in condensed matter physics at Brown is very active across many topics, including strongly correlated electronic systems, spintronics, quantum liquids and solids, superconductivity, nanoscale physics, quantum phase transitions, ultrafast and quantum optics, semiconductor physics and devices, low temperature detectors, and soft condensed matter. Application materials including a curriculum vita, a statement of research and teaching plans, and three letters of recommendation should be submitted electronically to https://secure.interfolio.com/apply/21934. Inquiries about this position should be directed to Phys-search@brown.edu or to **Prof. Gang Xiao, Chair of Condensed Matter Physics Search Committee, Department of Physics, Box 1843, Brown University, Providence, Rhode Island 02912.** Applications received by **December 1, 2013** will receive full consideration. *Brown is an EEO/AA employer. Minorities and women are encouraged to apply.* C1113019

University of Idaho, Department of Physics
TENURE-TRACK FACULTY POSITION
Biophysics

The Department of Physics at the University of Idaho invites applications for a tenure-track faculty position in the area of experimental biophysics at the level of Assistant Professor starting in 2014 Fall. This position is part of the College of Science's interdisciplinary cluster of hires focused on systems biology, as defined by the NIH (http://www.nigms.nih.gov/Research/FeaturedPrograms/SysBio/). The successful candidate will be expected to build a successful research program, teach and advise students, and contribute to the college's strategic interdisciplinary initiative in systems biology. Minimum qualifications include a PhD in Physics, Biophysics, or a related field; specialization in experimental biophysics; and the ability to teach undergraduate and graduate physics courses. Postdoctoral experience, a strong publication record, and the potential to secure external funding are desirable. Competitive startup funds are available. Candidates must submit all application materials online at http://apptrkr.com/382264. Information about the UI Department of Physics can be found at http://www.uidaho.edu/sci/physics. Questions should be addressed to **Dr. F. Marty Ytreberg** at ytreberg@uidaho.edu. To receive first consideration, please submit all application materials by **November 8, 2013**. Following initial review of the first consideration applicant pool, job posting may be re- posted and/or un-posted until position is filled. *The University of Idaho is an Equal Opportunity and Affirmative Action Employer. Women and minorities are strongly encouraged to apply.* 3020

Faculty Position, School of Physics - Georgia Tech
Georgia Institute of Technology

Tenure-Track Faculty Position School of Physics Georgia Institute of Technology The School of Physics of the Georgia Institute of Technology invites applications for a tenure-track, Assistant Professor position beginning Fall 2014. Applications for an Associate or Full Professor level position may also be considered for exceptionally qualified individuals. Targeted research areas are: Experimental and Observational Astrophysics (including Astro-Particle and Gravitational Wave Physics), and Experimental and Theoretical Condensed Matter (including Hard and Soft). Successful applicants are expected to direct an active program of funded research and to teach effectively at both the undergraduate and graduate levels. Applicants should email to faculty.search@physics.gatech.edu the following documents in PDF format: 1) cover letter, 2) curriculum vitae including a full list of publications and relevant teaching experience, 3) a research plan for the next five years (maximum 3 pages), and 4) a statement of teaching philosophy and experience (maximum 1 page). In addition, junior applicants should arrange to have three letters of reference emailed separately to the same address. Review of applications will begin **December 1, 2013**. *Georgia Tech is a unit of the University System of Georgia and an equal education/employment opportunity institution.*
1943643

University of Vermont
Assistant Professor of Physics

The University of Vermont invites applications for a tenure-track faculty position in experimental condensed matter/materials physics at the Assistant Professor level, with a starting date of August 2014. The University of Vermont is the principal research institution in Vermont and is currently in a period of dynamic growth. The University of Vermont recently identified three "Spires of Excellence" in which it will strategically focus institutional investments and growth over the next several years (uvm.edu/~tri/). These include Neuroscience, Behavior and Health; Complex Systems; and Food Systems. Candidates whose research, scholarship, and/or creative work align or intersect with the Complex Systems Transdisciplinary Research Initiative (see uvm.edu/~cmplxsys/) are especially encouraged to apply. Applicants must have a Ph.D. in physics, postdoctoral research experience, and outstanding potential to perform research in experimental condensed matter/materials physics. The successful candidate will develop a vigorous sponsored research program, teach at all levels, and advise undergraduate and graduate master's and doctoral students, in addition to professional contributions and service. Apply online at uvmjobs.com. Search for the position using department name (Physics) only. Attach a cover letter, curriculum vitae, statements of research and teaching philosophy, and the names of three professional references. For more information contact the **Physics Faculty Search Committee, Physics Department, Cook Building, University of Vermont, Burlington VT 05405-0125.** Review of applications will begin on **December 1, 2013** and will continue until the position is filled. The Department is interested in candidates who can contribute to the diversity and excellence of the academic community through their research, teaching, and service. Applicants are requested to include in their cover letter information about how they will further this goal. *The University of Vermont is an Affirmative Action/Equal Opportunity employer. The Department is committed to increasing faculty diversity and welcomes applications from women and underrepresented ethnic, racial and cultural groups; from people with disabilities; and from people with international backgrounds.* C1113023

THEORETICAL CONDENSED MATTER AND STATISTICAL PHYSICS (CM&SP)
POST-DOCTORAL POSITIONS AT
THE ABDUS SALAM
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS (ICTP)
(ACADEMIC YEAR 2014-2015)

The current research areas of the ICTP CMSP Section include disordered quantum many-body systems, quantum Monte Carlo simulations of ultra-cold gases: BEC-BCS crossover in strongly interacting Fermi gases, low-dimensional and/or disordered Bose gases; physics of nano-devices; statistical physics of complex systems and interdisciplinary applications; random matrix theory and its applications; density functional theory based investigations of structural, electronic and optical properties of materials, in particular in the field of renewable energy storage and conversion; development of efficient algorithms for the computation of electronic excitations in nanoscale systems. A limited number of post-doctoral positions for young CM&SP theoreticians will be available starting Fall 2014. Appointments will be made for two years, with the possibility of renewal for one more year. Applicants should be no more than 35 years of age at the time of application and should have obtained their Ph.D. after 2009. The application form can be accessed at the website: https://onlineapps.ictp.it/ENTER/APPLICANT/CP13.mhtml. Additional detailed curriculum vitae, list of publications and at least three recommendation letters (sent separately after submission of application) must all be appended on-line. Deadline for receipt of applications: **12th January 2014**. C1113026

Winthrop Physics Assistant Professor tenure-track opening for Aug 2014 in ACS-approved program (chem.winthrop.edu) at top tier school near Charlotte. Chosen applicant will team with one other physics, three geology, and 12 chemistry faculty to mentor undergraduate research and will primarily teach undergraduate physics lectures and labs. Qualifications include PhD in physics or very closely-related discipline; passion for mentoring undergraduate research; expertise to teach undergraduate physics; potential for undergraduate teaching; recent research publications; and expertise in area that matches interests and complements current strengths. Email letter, CV, transcripts, teaching philosophy, teaching interests, undergraduate research interests, and 3 recommendations to physics@winthrop.edu by **December 6, 2013**. C1113011

Assistant Professor of Physics, Worcester State University

Worcester State University, Department of Physical and Earth Sciences, invites applications for a tenure-track position at the Assistant Professor level in Physics beginning in Fall 2014. Minimum requirements include a Ph.D. in Physics or Astronomy and undergraduate teaching experience; postdoctoral research experience is preferred. We are particularly interested in applicants trained in astrophysics or astronomy, although applicants in all subfields will be considered. In addition to teaching physics, the successful candidate may teach integrated science courses for education majors and develop new freshman seminars. Applicants should demonstrate: potential for excellence in teaching and mentoring undergraduate students; engagement in research and scholarship; a commitment to public higher education; enthusiasm for developing the physics curriculum and interdisciplinary science programs; an interest in science education. The successful candidate will help shape a small, dynamic department dedicated to offering a quality liberal arts education and small class sizes in a public institutional setting. Our department offers bachelor's degrees in Natural Science and Geography, and a minor in Physics. Worcester State University is part of the Massachusetts state system. The contractual teaching load is 12 contact hours per semester. The position includes full state benefits. Review of applications will begin **December 1, 2013**. All applicants will apply online through http://worcester.interviewexchange.com. Necessary documents for submission include a cover letter, CV, three letters of reference signed by hand and dated within the last six months, and an official (non-student issued) transcript of highest degree. Those documents which cannot be uploaded to one's e-account may be sent to the following address: **Director of Human Resources, Worcester State University, 486 Chandler Street, Worcester, MA 01602-2597.** For more information please email **Johanie** at jrodriguez7@worcester.edu. C1113027

Stanford University Faculty Positions

1. Experimental Condensed Matter Physics. The Department of Physics at Stanford University seeks applicants for a faculty position in the area of experimental condensed matter physics, broadly defined. We particularly encourage applicants at the tenure track Assistant Professor level, but are prepared to consider exceptional candidates at more senior levels: Associate Professor (tenured or tenure track), or Professor (tenured). Applicants should exhibit the potential (if tenure track) or a demonstrated track record (if tenured) of running a world-recognized independent research program, and should also possess good communication skills and a commitment to teaching and education. The term of appointment would begin on or around September 1, 2014. Applicants must send materials to the search committee, chaired by Prof. David Goldhaber-Gordon, through AcademicJobsOnline. Candidates should upload a cover letter, curriculum vitae, publication list, a research and teaching statement (three page combined maximum), and arrange to have three letters of reference submitted online at https://academicjobsonline.org/ajo/jobs/3089. Inquiries may be directed to **J. Tice, Dept. of Physics, 382 Via Pueblo Mall, Stanford University, Stanford, CA 94305-4060,** or to tice@stanford.edu. The due date for submission of all materials, including letters of reference, is **December 1, 2013**.

2. Experimental Physics: Fundamental Interactions. The Department of Physics at Stanford University is seeking applicants for a faculty position in the area of experimental physics with a focus on fundamental particles and interactions. The search is "open" as to the level of appointment; we encourage applicants for tenure track Assistant Professor, Associate Professor (tenured or tenure track), and Professor (tenured) appointments. Areas of interest include but are not limited to particle physics, particle astrophysics, gravitational physics and precision measurements. Applicants will be expected to teach physics courses at both the graduate and undergraduate levels. The term of appointment would begin on or around September 1, 2014. Applicants must send materials to the search committee, chaired by Professor Patricia Burchat, through AcademicJobsOnline. Candidates should upload their curriculum vitae, publication list, a research & teaching statement (three pages combined maximum), and arrange to have three letters of reference submitted online at https://academicjobsonline.org/ajo/jobs/3088. Inquiries may be directed to: **Fund. Particles & Interactions search, J. Tice, Physics Dept., 382 Via Pueblo Mall, Stanford University, Stanford, CA 94305-4060** or to tice@stanford.edu. The due date for the submission of all materials, including letters of reference, is **December 1, 2013**.

Stanford University is an equal opportunity employer and is committed to increasing the diversity of its faculty. It welcomes nominations of, and applications from, women and members of minority groups, as well as others who would bring additional dimensions to the university's research and teaching missions. C1113032

Faculty Positions at National Central University, Taiwan

The Department of Physics invites applications for tenured or tenure track positions in general areas of physics, starting from August 2014. A successful candidate is expected to establish a strong and independent research program, obtain research funding, commit to excellent teaching, and supervise students. Applicants should submit a curriculum vita and research prospectus, and arrange three reference letters to be sent to: **Prof. Shih-Hung Chen, Department of Physics, National Central University, Jhongli City, Taoyuan County 32001, Taiwan (e-mail: chensh@ncu.edu.tw; tel: 886-3-4253749).** To ensure full consideration, applications should be received before **December 31st, 2013**. C1113031

Tenure-Track Assistant Professor of Physics and Astronomy (Experimental) Colby College

Colby College invites applications for a newly created tenure-track position in physics and astronomy, beginning September 1, 2014. We seek applicants with a commitment to excellence in both research and teaching at the undergraduate level. Applicants must have a Ph.D. in astronomy, astrophysics, or physics, and post-doctoral and teaching experience is preferred. Preference will be given to experimental physicists, astrophysicists and astronomers who plan to provide opportunities for on-campus involvement in their research and who will be able to teach a range of courses. The successful candidate will teach a variety of classes in the physics and astronomy curriculum. The new hire will join five other physicists with active on-campus research programs in experimental astrophysics, experimental atomic physics, theoretical particle physics, and experimental condensed matter physics, and we are especially interested in candidates who will complement the research areas of existing faculty at Colby. Members of the department teach courses for non-science majors, introductory courses for science majors, and courses for physics majors. Faculty members also supervise capstone research projects that are required of all senior physics majors. Laboratory instruction is shared by all members of the department. More information about Colby's physics and astronomy program can be found at http://www.colby.edu/physics/. The department has a teaching assistant, and shares an electronics technician/machinist and a scientific computing support administrator with other departments. The College encourages the attendance of its faculty at professional meetings by providing funds for travel. Institutional grants are available within the Colby College Science Division to provide support for research, research travel, and publication costs. Significant research start-up funding is available. Applicants should submit curriculum vitae, descriptions of teaching experience and interests, and descriptions of research (including publications) electronically to physicssearch@colby.edu, and arrange to have three letters of reference sent to the same address. Application materials should be addressed to **Professor Duncan Tate, Chair, Department of Physics and Astronomy, Colby College.** Review of applications will begin **December 16, 2013** and will continue until the position is filled. *Colby College is committed to equality and diversity and is an equal opportunity employer. We encourage inquiries from candidates who will contribute to the cultural and ethnic diversity of our college. Colby College does not discriminate on the basis of race, gender, sexual orientation, disability, religion, ancestry or national origin, or age in employment or in our educational programs.* For more information about the College, please visit our website: www.colby.edu. 1943599

Tenure-Track Faculty Position in Physics
Physics Department
United States Naval Academy

The Naval Academy's Physics Department invites applications for a tenure-track faculty position in physics starting as early as fall 2013. Appointments at all ranks will be considered, but the preference is for junior faculty at the rank of Assistant Professor. Candidates in all fields who value a balance between teaching and research are encouraged to apply. Particularly attractive opportunities exist for candidates who specialize in the condensed matter area of dielectric/electrical properties of materials. Visit http://usna.edu/PhysicsDepartment for more information. Send a cover letter, a CV, unofficial graduate and undergraduate transcripts, the names of three references, a statement of teaching philosophy, and research plans to search@usna.edu. *The U. S. Naval Academy is an Equal Opportunity Employer.* C1113014

Faculty Position in Theoretical or Computational Biophysics
Emory University

The Department of Physics at Emory University invites applications for a tenure-track faculty position in theoretical or computational biophysics, to begin in September 2014. The position is at the assistant professor level, but senior appointments may be considered in exceptional circumstances. We are particularly interested in applicants who will benefit from and complement the existing strengths in cellular and molecular biophysics, computational neuroscience, and population biology in the Physics and other Departments at Emory. Applicants must have a PhD in physics or a closely related field and a proven record of research accomplishment. The successful candidate will be expected to establish an independent, internationally recognized and externally funded research program, and demonstrate excellence in teaching at both undergraduate and graduate levels. To apply, submit a curriculum vitae, a research plan, and a teaching statement to search-biophysics-2013@physics.emory.edu. Applicants should arrange for at least three letters of recommendation to be sent to the same address. To ensure full consideration, complete applications, including recommendation letters, should be received by **December 1, 2013**. *Emory University is an Affirmative Action/Equal Opportunity employer. Women and members of underrepresented groups are particularly encouraged to apply.* 1950841

Hiring Professors at All Ranks at
South University of Science and Technology (SUSTC) Shenzhen, China

The South University of Science and Technology (SUSTC) invites applications and nominations for all ranks of tenured and tenure-track faculty members in the Division of Science, Division of Engineering and Division of Management & Finance. SUSTC, officially established in April 2012, is a public institution funded by the municipal of Shenzhen, a special economic zone city in southern China. The University is accredited by the Ministry of Education, China and is a pioneer in higher education reform in China. Set on five hundred acres of wooded landscape in the picturesque Nanshan (South Mountain) area, the new campus offers an idyllic environment suitable for learning and scholarship. SUSTC engages in basic and problem-solving research of lasting impact to benefit society and mankind. The Division of Science, Division of Engineering, and the Division of Management & Finance wish to hire faculty members at all ranks. Key areas include but not limited to: Neural and Cognitive Sciences, Biology and Gene Engineering, Modern Physics, Control and Modification of Materials, Nanoscience and Nanotechnology, Mathematics and Applied Mathematics, Molecular Chemistry and Catalysis, Large-Scale Computational Research, Robotics and Artificial Intelligence, Information Systems and Electronic Engineering, Modern Cities and Future Developments, Energy Sciences and Technology, Environmental Sciences, Financial Mathematics and Management Sciences. The Divisions especially encourage research that requires a multi-disciplinary approach. Experienced researchers whose interests do not fall within the above areas are invited to suggest new areas of research. Cluster hiring is possible, with senior members accompanied by junior members in a group. The teaching language at SUSTC is English or Putonghua. The choice is made by the instructor. As we expect an international faculty, the majority of teaching materials and reference books will be in English and many classes will be conducted in English. With a very high faculty-to-student ratio, SUSTC is committed to delivering a student-centered education and encourages students to develop their innovative spirits. Students at junior and senior years are expected to participate in research in the Research Centers. The University offers competitive salaries, fringe benefits including medical insurance, retirement and housing subsidy. Leading Professors, Chair Professors and Professors will be appointed with tenure. Associate Professors and Assistant Professors will be offered tenure-track contracts. Send nominations, inquiries and applications to: hiring@sustc.edu.cn. All applications should include a CV and a detailed list of publications. Those interested in cluster hiring should send CVs and publication lists as a group. Evaluations will commence immediately and appointments will be made on a continuous basis. Additional information on SUSTC is available on the University homepage http://www.sustc.edu.cn/ and http://english.sina.com/china/2012/0902/502496.html. Qualified applicants are also encouraged to apply for the Recruitment Program of Global Expert ("Thousand Talents Program") through SUSTC. Successful applicants will get extra research fund and living allowance from the government. Additional information is available through email inquiry or http://talent.sustc.edu.cn/cn/jobgc.aspx?sign=635058515051562045. 1919596

Tenure-Track Assistant Professor Position at Temple University

The Physics Department at **Temple University** invites applications for a tenure-track assistant professor position, starting September 2014. The department is seeking an outstanding experimentalist in the area of materials physics with the potential for excellence in research and teaching. Applicants must have a Ph.D. in physics. To apply please send a curriculum vitae, publication list, research plan, statement of teaching philosophy, and arrange to have three letters of recommendation all on-line: https://phys.cst.temple.edu/. Application deadline is **January 15, 2014**. However, the search will remain open until the position is filled. *Temple University is exceedingly diverse in all aspects of University life and is an Equal Opportunity/Affirmative Action Employer.* C1113033

KAVLI INSTITUTE FOR THEORETICAL PHYSICS

Future Programs

During the years 2014/2015, the Kavli Institute for Theoretical Physics will conduct research programs in the following areas:

- **Frontiers of Intense Laser Physics**
  Andre Bandrauk, Katarzyna Krajewska, Anthony Starace*
  July 21, 2014 – September 19, 2014
- **Evolution of Drug Resistance**
  Richard Neher, Ville Mustonen, Daniel Weinreich*
  July 21, 2014 – September 19, 2014
- **Magnetism, Bad Metals, and Superconductivity: Iron Pnictides and Beyond**
  Piers Coleman, Peter Hirschfeld, Srinivas Raghu, Qimiao Si*
  September 2, 2014 – November 21, 2014
- **Avalanches, Intermittency, and Nonlinear Response in Far-From-Equilibrium Solids**
  Karin Dahmen, Pierre Le Doussal, Corey O'Hern*
  September 22, 2014 – December 12, 2014
- **Present and Future Neutrino Physics**
  Graciela Gelmini, Danny Marfatia, Thomas Weiler, Walter Winter*
  September 29, 2014 – December 19, 2014
- **Galactic Archaeology and Precision Stellar Astrophysics**
  Jo Bovy, Charlie Conroy, Juna Kollmeier, Marc Pinsonneault*
  January 12, 2015 – April 3, 2015
- **Dynamics and Evolution of Earth-Like Planets**
  Eric Ford, Louise Kellogg, Geoff Marcy, Burkhard Militzer*
  January 20, 2015 – March 26, 2015
- **Quantum Gravity Foundations: UV to IR**
  Ben Freivogel, Steve Giddings, Ted Jacobson, Juan Maldacena*
  March 30, 2015 – June 19, 2015
- **Entanglement in Strongly-Correlated Quantum Matter**
  Tarun Grover, Matthew Headrick, Roger Melko*
  April 6, 2015 – July 3, 2015
- **Deconstructing the Sense of Smell**
  Maxim Bazhenov, Alex Koulakov, Venkatesh Murthy, Anne-Marie Oswald*
  June 8, 2015 – July 31, 2015

The Institute has a small number of openings, for a duration of less than one year, for general visitors not attached to the above-listed programs.

Physicists wishing to participate in any of the Institute's activities should apply through our web page at http://www.kitp.ucsb.edu or write to:

Professor Lars Bildsten, Director
Kavli Institute for Theoretical Physics
University of California
Santa Barbara, CA 93106-4030

The Institute invites suggestions either for short programs (3 months) or long programs (5-6 months) for the years 2015-2016 and later.

*Coordinators

The University of California, Santa Barbara, is an equal opportunity/affirmative action employer.

The **Faculty of Mathematics and Natural Sciences at the University of Cologne** invites applications for the position of a

Full Professorship (W3) for Experimental Physics Condensed Matter Physics (Physics Institute II)

Candidates should have an outstanding research record in experimental condensed matter physics that expands and complements the ongoing research activities at the Department of Physics at the University of Cologne. He/She should play a leading role in condensed matter research at the University of Cologne. Possible research areas include topological matter, interfaces and/or thin films, control of quantum matter, or strongly correlated electron systems. The new professor is expected to teach physics both at the undergraduate and the graduate level, and to be actively involved in the Bonn-Cologne Graduate School of Physics and Astronomy.

The professorship will be integrated into the University's Center of Excellence on "Quantum Matter and Materials" (QM^2). QM^2 is a focused strategic alliance between theoretical physics, experimental physics, chemistry, and mathematics and integrates scientists and research institutions in the Cologne area. It is strongly supported by the University's master plan and by the Excellence Initiative of the German federal and state governments.

Qualification requirements are in accord with the North Rhine-Westphalia University Law and include an excellent track record in research and teaching. Women are strongly encouraged to apply.

The University of Cologne is an equal opportunity employer in compliance with the German disability laws. Applications should include a letter of motivation with a teaching and research statement and the usual documents (CV, complete publication list highlighting the 5 most important papers, information on external funding, academic achievements and honors, and 3 references) as well as a completed form provided at http://www.mathnat.uni-koeln.de/mnfapplication.html.

Applications should be submitted preferably via e-mail no later than **December 1, 2013** to: **Professor Dr. Karl Schneider, Dean of the Faculty of Mathematics and Natural Sciences, University of Cologne, Albertus-Magnus-Platz, 50923 Cologne, Germany, e-mail: mnf-berufungen@uni-koeln.de**

www.uni-koeln.de

Universität zu Köln

UNIVERSITY *of* NEW HAMPSHIRE

Peter T. Paul Chair in Space Sciences

The University of New Hampshire's College of Engineering and Physical Science (CEPS) and the Institute for the Study of Earth, Oceans, and Space (EOS) seek an outstanding individual to fill the Peter T. Paul Chair in the Space Science Center. This tenure-track position will most likely reside in the Department of Physics, although an affiliation with another department within CEPS is also possible. The rank will be commensurate with experience. The Chair includes an annual research stipend that may be used for graduate students, post-graduates, or equipment support. The Space Science Center conducts research in a wide range of fields that include solar, heliospheric, magnetospheric, ionospheric, and planetary physics, as well as high-energy astrophysics. The Space Science Center has a strong history in the development of space flight instrumentation. On-site facilities and an experienced staff of engineers are available to support ongoing experimental efforts. The Center also hosts vibrant theory and simulation groups that complement the experimental programs.

Candidates for this position must have the ability and desire to participate in graduate and undergraduate education and to lead a major, independent research effort in a field that is aligned with any of the current research programs. Applicants must have a Ph.D. in Physics, Astronomy, Engineering or a related field, and seven or more years of professional research experience beyond the Ph.D. The candidate should demonstrate an ability to lead in an increasingly diverse cultural, social and ethnic community. Review of applications will begin on Dec. 1, 2013. Applicants should submit their application as a PDF document containing a cover letter, a curriculum vitae, and brief summaries of teaching interests and future research plans, to **Robbin.Williams@unh.edu**. The applicant should also arrange for three letters of reference to be sent to the same address. Inquiries about the position should be directed to Prof. Lynn Kistler, Director, Space Science Center, at **Lynn.Kistler@unh.edu**.

The University of New Hampshire is an Equal Opportunity/Equal Access/Affirmative Action institution. The University seeks excellence through diversity among its administrators, faculty, staff, and students. The university prohibits discrimination on the basis of race, color, religion, sex, age, national origin, sexual orientation, gender identity or expression, disability, veteran status, or marital status. Application by members of all underrepresented groups is encouraged. For a more comprehensive job description, visit **http://jobs.usnh.edu**; posting **# 0901906**.

New Faculty Position in Theoretical Plasma Physics

The Department of Physics at **Auburn University** is seeking a qualified individual for a tenure-track faculty position in theoretical plasma physics. Applicants must have a Ph.D. or equivalent degree and post-doctoral research experience is highly desirable. The successful candidate will be expected to: (1) actively develop their own research program in theoretical/computational plasma physics related to either fusion or basic laboratory plasmas, (2) interact with and contribute to the advancement of the experimental plasma physics programs at Auburn University, (3) advise and mentor undergraduate, graduate student and post-doctoral researchers in plasma physics, and (4) have a strong commitment to high quality teaching and teach both Graduate and Undergraduate students. Interested candidates should submit a letter of interest, a curriculum vitae; and the names of three references. Review of applications will begin **January 1, 2014** and will continue until the position is filled. The desired starting date is August 16, 2014. In order to apply for this position and view full details, please visit our online website at https://aufacultypositions.peopleadmin.com/postings/240. *The candidate selected for this position must be able to meet eligibility requirements to work in the United States at the time the scheduled appointment begins and to continue working legally for the proposed term of employment. The candidate must have excellent communication skills. Auburn University is an affirmative action, equal opportunity employer. Minorities and women are encouraged to apply.* C1113039

Visiting Assistant Professor of Physics Hamilton College

The Physics Department at Hamilton College seeks applicants for a 2-year visiting position beginning in July 2014. PhD required. The successful candidate will be comfortable teaching at the introductory and advanced levels, in both classroom and laboratory settings. Your cover letter should address the ways in which you would further the College's goal of building an inclusive educational environment. Previous experience teaching or working with diverse student populations is an asset. Information on the Physics department may be found at http://physerver.hamilton.edu/. Applicants should submit a c.v., statements of teaching and research interests, and arrange for submission of three letters of reference to https://secure.interfolio.com/apply/22069. Questions may be directed to **Professor Gordon Jones,** gjones@hamilton.edu. Review of materials will begin **January 6, 2014**, but applications will be accepted until the position is filled. *Hamilton College (www.hamilton.edu) is a residential liberal arts college located in upstate New York. Applicants with dual-career considerations can find other Hamilton and nearby academic job listings at www.upstatenyherc.org. Hamilton College is an affirmative action, equal opportunity employer and is committed to diversity in all areas of the campus community. Hamilton provides domestic partner benefits. Candidates from underrepresented groups in higher education are especially encouraged to apply.* C1113035

Cowen Chair in Experimental Condensed Matter Physics Michigan State University

The Department of Physics and Astronomy at Michigan State University is looking for an outstanding physicist to fill the Cowen Endowed Chair in Experimental Physics. The position may be filled at any level: exceptional junior or early-career candidates are encouraged to apply. The Chairholder is expected to generate a world-class research program and to have aptitude for teaching. Research in all areas of modern condensed matter physics will be considered, but the department is especially interested in enhancing its efforts in the nascent areas of quantum dynamics and transport of nanoscale systems, as well as quantum measurement and control. This position can be found on the MSU Applicant Page (http://www.hr.msu.edu/hiring/msujobs.htm), posting #8394. Applications must be uploaded to MSU's online job application site, https://jobs.msu.edu/, and should include a cover letter, CV, statement of research plans, and one-page teaching statement. In addition, three letters of recommendation must be submitted electronically by the recommenders through the application system. Senior candidates should include the names of at least two additional references on their CVs. Complete applications should be received by **December 1, 2013**, but review of applications will continue until the position is filled. Questions regarding this position may be directed to the search committee chair, **Prof. Norman Birge**, at birge@pa.msu.edu. *MSU is an affirmative action, equal opportunity employer and is committed to achieving excellence through a diverse workforce and inclusive culture that encourages all people to reach their full potential. The university actively encourages applications and/or nominations of women, persons of color, veterans and persons with disabilities. MSU is committed to providing a work environment that supports employees' work and personal life, and offers employment assistance to the spouse or partner of candidates for faculty and academic staff positions.* C1113038

FACULTY POSITION IN EXPERIMENTAL ATOMIC, MOLECULAR, AND OPTICAL PHYSICS - Purdue University

The Department of Physics at Purdue University (www.physics.purdue.edu) seeks applications for a faculty position at the rank of Assistant Professor in the area of experimental atomic, molecular, and optical physics. Applicants must have a Ph.D. in physics or a related field, an outstanding record of research accomplishments, and evidence of potential excellence in teaching at both the undergraduate and graduate levels. Salary and benefits are highly competitive. Candidates are expected to develop a vigorous research program, supervise graduate students, and teach undergraduate and graduate courses. Interested candidates should submit their curriculum vitae, publication list, brief descriptions of their planned research program and teaching philosophy, and a list of three references. Electronic submission is preferred: https://www.physics.purdue.edu/searches/app/. Questions regarding the position and search should be directed to Chris Greene at chgreene@purdue.edu. Applications completed by **January 13, 2014** will be given full consideration, although the search will continue until the position is filled. *Purdue University requires a background check for employment in all positions. Purdue University is responsive to the needs of dual career couples, has received an NSF ADVANCE Award, and is dedicated to work life balance through an array of family friendly policies. Purdue University is an Equal Opportunity/Equal Access/Affirmative Action employer and is committed to building a diverse faculty of excellence.* C1113136

Faculty and Research Scholar Positions Center for Condensed Matter Sciences National Taiwan University

The Center for Condensed Matter Sciences, a premiere research center at National Taiwan University, has immediate openings for regular faculty and non-tenure research scholar positions. Rank of faculty positions will match with the candidate qualifications. Applicants with excellent credentials in cutting edge condensed matter research fields of electronic, optical, spintronics, quantum transport, nanostructured and energy materials, as well as spectroscopies and microscopies, in both basic and applied aspects, will be considered. Applicants should send resume, publication list, research plans and three letters of recommendation to: **Director, Prof. Li-Chyong Chen, Center for Condensed Matter Sciences, National Taiwan University, Taipei 106, Taiwan, Center Assistant: Wei-Lin Chou,** Email: cwli1828@ntu.edu.tw, Phone: (02) 3366-5201, Fax: (02) 2365-5404. Closing date for applications is **Dec. 15, 2013**. C1113041

FACULTY POSITION IN THEORETICAL BIOLOGICAL PHYSICS Purdue University

The Department of Physics at Purdue University (www.physics.purdue.edu) seeks applications for a faculty position at the rank of Assistant Professor in the area of theoretical biological physics. Applicants must have a Ph.D. in physics, biophysics or a related field, an outstanding record of research accomplishments, and potential for excellence in teaching at both the undergraduate and graduate levels. Salary and benefits are highly competitive. Candidates are expected to develop vigorous research programs, supervise graduate students, and teach undergraduate and graduate courses. Interested candidates should submit their curriculum vitae, publication list, and brief descriptions of their planned research program and teaching philosophy. Electronic submission is preferred: https://www.physics.purdue.edu//searches/app/. At least three letters of recommendation should be sent to **Biophysics Search, Department of Physics, Purdue University, 525 Northwestern Ave., West Lafaytte, Indiana 47907-2036, USA.** Applications completed by **December 1, 2013** will be given full consideration, although the search will continue until the position is filled. A background check is required for employment in this position. *Purdue University requires a background check for employment in all positions. Purdue University is responsive to the needs of dual career couples, has received an NSF ADVANCE Award, and is dedicated to work life balance through an array of family friendly policies. Purdue University is an Equal Opportunity/Equal Access/Affirmative Action employer fully committed to achieving a diverse workforce of excellence.* C1113037

Faculty Position in Condensed Matter Theory University of Pittsburgh Department of Physics and Astronomy

The Department of Physics and Astronomy at the University of Pittsburgh (http://www.physicsandastronomy.pitt.edu/) invites applications for a new faculty member in Theoretical Condensed Matter Physics. This appointment, which is subject to budgetary approval, will be in the tenure stream at the Assistant Professor level and will begin with the Fall Term 2014, or thereafter. While applications over a wide range of specialties are encouraged, the successful candidate will enhance or strategically complement existing theoretical and experimental programs in our department. There will be some preference given to applications of those working in the following areas: Quantum Physics at the Interface of Physics, Biology and Quantum Information; Statistical Physics, Biophysics and Soft Condensed Matter; Strongly Correlated Systems; Quantum Gases. If appropriate, the successful candidate would be associated with the newly established Pitt Quantum Initiative (http://www.pqi.pitt.edu). All candidates should have the potential to teach effectively at both the graduate and undergraduate levels and to attract external funding for a creative, independent and broad- based research program. To ensure full consideration, complete applications should be received by **November 15, 2013**. However, applications will be accepted for the duration of the search. Applicants should email PDF documents (preferably a single document) containing a cover letter, curriculum vitae, bibliography, statement of research interests, and brief teaching statement to pasearch+cmt@pitt.edu. In addition, applicants should arrange to have at least three letters of reference sent to: **CM-Theory Search Committee, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260.** *The University of Pittsburgh is an Affirmative Action, Equal Opportunity Employer. Women and members of minority groups under-represented in academia are especially encouraged to apply.* C1113042

Faculty Positions in Theoretical Condensed Matter Physics University of Virginia

The University of Virginia Physics Department is planning to hire **two faculty members** doing research in condensed-matter theory, broadly construed. We welcome applications from theorists with a strong and independent research record in traditional condensed-matter physics and/or areas with overlap with atomic physics, quantum information, field theory and mathematics. We expect also a strong interest in teaching and mentoring students. For one of the positions, our intent is to hire a candidate with substantial computational expertise as well. Those hired will be expected to establish a successful research program as well as teach at the undergraduate and graduate levels. The appointments are planned for the tenure-track Assistant Professor position level, but a higher-level appointment may be considered in exceptional cases. Review of applications will begin **December 2, 2013**. Applicants must have earned a Ph.D. in physics or related field at the time of application. The appointment start date is August 25, 2014. To apply candidates must submit a Candidate Profile through Jobs@UVa (https://jobs.virginia.edu), search on posting number **0612825** and electronically attach the following: a curriculum vitae, a statement describing the proposed research agenda, contact information for at least three references, and a cover letter. Please have the references email letters directly to phys-cm-theo-pos@virginia.edu . Questions regarding the application process to JOBS@UVa should be directed to **Tammie Shifflett,** tms4t@virginia.edu, 434-924-6565. *The University will perform background checks on all new faculty hires prior to making a final offer of employment. The College of Arts and Sciences and the University of Virginia welcome applications from women, minorities, veterans and persons with disabilities; we seek to build a culturally diverse, intellectual environment and are committed to a policy of equal employment opportunity and to the principles of affirmative action in accordance with state and federal laws.* C1113040

ASU

Assistant Professor (Job#10569)
Faculty Position in XFEL Biophysics
Department of Physics, Arizona State University

The Department of Physics at Arizona State University (ASU) seeks applicants for a tenure-track faculty position at the assistant professor level in the application of X-ray lasers to biology and related theory, instrumentation, and technique or algorithm development to begin Fall 2014. The successful applicant will become part of an interdisciplinary team at ASU that aims to solve important biological questions using the expanding global network of free-electron X-ray laser facilities. The successful candidate will be expected to develop a vigorous externally-funded research program at ASU with significant national and international recognition; teach effectively at the undergraduate and graduate levels; participate in professional and university service; and collaborate with the team of ASU faculty supported by a new BioFEL National Science Foundation-Science and Technology Center (STC) and work collaboratively in the STC—a consortium of six universities across the U.S.A complementary faculty search is also underway in the ASU Department of Chemistry and Biochemistry.

ASU is in the Phoenix metropolitan area in Tempe, Arizona and is one of the largest universities in the U.S. Recently ranked as one of the top 100 research universities in the world, its 40 physics faculty work mainly in Biophysics, Nano and Materials Science, and Cosmology and Particle Astrophysics. More information on ASU Physics faculty and their achievements can be found at **http://physics.asu.edu**. ASU is also home to both the Beyond Center (**http://beyond.asu.edu**) and the Origins Institute (**http://origins.asu.edu**).

Minimum Qualifications:
- Doctorate in field relevant to physics or biophysics
- Demonstrated potential to establish a vigorous, externally-funded research program.
- A strong record of research accomplishments
- A strong commitment to excellence in teaching.

Desired Qualifications:
- Postdoctoral experience
- A strong commitment to working in an interdisciplinary environment.

To apply, please submit as a single PDF document: (1) a cover letter which includes the names and email addresses of three references, (2) a curriculum vitae with a list of publications, (3) a succinct outline of future research plans, and (4) a statement of teaching philosophy and interests. PDF application materials should be submitted via the employment application portal found at **http://physics.asu.edu/employment.** The applicant should arrange for the three references identified in the cover letter to upload letters of recommendation to the employment portal listed above.

Applications will be reviewed beginning **November 12, 2013** with review of applications continuing weekly until the search is closed. *A background check is required for employment. Arizona State University is an equal opportunity/affirmative action employer and is committed to excellence through diversity. Women and minorities are encouraged to apply.* **www.asu.edu/titleIX**

MIT LINCOLN LABORATORY

Newly Announced Opportunities

POSTDOCTORAL ASSOCIATES

• Superconducting Qubits

Design and fabricate qubits within a team developing the foundation and major components of a quantum processor using superconducting circuits. You can expect access to excellent fabrication facilities; well-equipped measurement labs with five dilution refrigerators; ample technical support; and outstanding opportunities for interaction and collaboration with both Laboratory and MIT staff. Requirements include a Ph.D. in Physics or related field, at least three years of experimental work on superconducting qubits and excellent programming skills, with expertise in LabVIEW, Python and MATLAB. **Req. 4280**

• Trapped-ion Quantum Information Processing

Join an effort with the long-term goal of developing technologies to enable large-scale quantum processing with individual atomic ions. Near-term research is focused on methods to enhance the speed and fidelity of quantum operations and techniques to generate large arrays of ions. Requirements include a Ph.D. in physics or related field and at least three years performing research in experimental atomic physics and/or quantum information processing. You should have experience with atomic laser cooling and trapping, UHV systems, cryogenic techniques, laser systems and optics, and experimental automation and control. **Req. 4281**

Positions are located in Lexington, MA.
To apply, please visit www.ll.mit.edu/employment

As an Equal Opportunity Employer, we are committed to realizing our vision of diversity and inclusion in every aspect of our enterprise. Due to the unique nature of our work, we require U.S. citizenship.

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

PENNSTATE
1855

Faculty Positions in Physics at Penn State

The Department of Physics at The Pennsylvania State University (University Park campus) anticipates making one or more faculty positions that will start in Fall 2014. We seek exceptional candidates in any of the department's current areas of research, which are AMO physics, astro-particle physics, biological physics, condensed matter physics, gravitational physics, and particle physics. Applicants should have a Ph.D. and an outstanding research record. Rank will be commensurate with qualifications and experience. Candidates should visit **www.phys.psu.edu/facapply**. A letter of application, a CV and a brief description of research plans will be required. Applicants for an assistant professorship should arrange for four letters of recommendation to be submitted. Applicants for a senior position should provide a list of at least six references, and may arrange for reference letters to be submitted.

Applications will be considered as they arrive. Those completed by **December 1, 2013** will be assured of full consideration. Later applications will be considered until the positions are filled. *Penn State is committed to affirmative action, equal opportunity and the diversity of its workforce.*

ASSISTANT PROFESSOR POSITION IN FUNDAMENTAL THEORY OF GRAVITY, COSMOLOGY, OR HIGH ENERGY PHYSICS
DEPARTMENT OF PHYSICS AND ASTRONOMY
UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL

We invite applications for an assistant professor position in the fundamental theory of gravity, cosmology, or high energy physics. Candidates should have demonstrated an excellent record of achievements, have broad interests and thorough training in either cosmology, gravitational, or high energy theory, including string theory, and have a commitment to high quality research and teaching. The Department intends to fill several positions in theoretical physics in the next few years. These new colleagues will complement our existing strengths in theoretical physics and be expected to play a major role in subsequent recruitment. The appointment is a regular tenure-track position. Interested applicants should submit a completed application at http://unc.peopleadmin.com/postings/32613, along with a Curriculum Vitae/Resume (which includes a cv and publication list), Research Statement, and Teaching Philosophy. Please also provide the names of four (4) referees to the above site. For timely consideration, please submit your application, and ensure your referees respond by **December 15, 2013**. Review of applicants will begin in December and continue until the position is filled. Address any inquires to theorysearch2014@listserv.unc.edu. We particularly encourage applications from members of under-represented groups. If you experience any problems accessing the system or have questions about the application process, please contact the University's Equal Employment Opportunity office at **(919) 966-3576** or send an email to equalopportunity@unc.edu. *Please note: The Equal Employment Opportunity office will not be able to provide specific updates regarding position or application status. The University of North Carolina at Chapel Hill is an equal opportunity employer.* C1113046

Tenure-track Position in Condensed Matter Physics

The Department of Physics and Astronomy at the **University of Alabama (Tuscaloosa)** invites applications for a tenure-track Assistant Professor position in Condensed Matter Physics (experimental or theoretical) with an emphasis on physics of confined systems. The appointment should begin 16 August 2014. The successful candidate is expected to collaborate with physics faculty in the highly successful, interdisciplinary MINT Center (mint.ua.edu) and/or other faculty in Chemistry and Engineering. In particular, the successful candidate's research expertise is expected to complement existing experimental work on the optical properties of low dimensional systems. The new faculty member would benefit from the extensive existing infrastructure at MINT and the UA Central Analytical Facility (caf.ua.edu) for general-purpose material characterization. More information can be found on the departmental (physics.ua.edu) and MINT websites. The minimum qualifications for this position are a Ph.D. in Physics or a related field and an outstanding record of research accomplishments. Postdoctoral experience is desirable. Candidates for this position are expected to have an outstanding research record and exhibit potential for effective teaching at the undergraduate and graduate levels. The successful candidate is expected to develop a high quality, externally funded research program, as well as teach and mentor at the undergraduate and graduate levels. We will begin reviewing applications on **December 1, 2013** and the review process will continue until the position is filled. Applications from women and minorities are strongly encouraged. Applications should consist of a resume, including descriptions of the applicant's accomplishments, research interests, teaching credentials and teaching philosophy, and arrange for three letters of reference to be sent electronically to rschad@bama.ua.edu or sent to the **Chair, Condensed Matter Search Committee, Department of Physics, Box 870324, The University of Alabama, Tuscaloosa, AL 35487.** Applications should be submitted online at facultyjobs.ua.edu/postings/34242. For additional information, contact the search committee chair, **Prof. Rainer Schad**, at **rschad@bama.ua.edu** or **+1 (205) 348-2404**. *The University of Alabama is an Equal Opportunity/Affirmative Action Employer, and actively seeks diversity among its employees.* C1113047

Tenure-track Position in Theoretical Elementary Particle Physics

The Department of Physics and Astronomy at the **University of Alabama, Tuscaloosa**, invites applications for a tenure-track position in theoretical elementary particle physics at the rank of assistant professor. The appointment will begin August 2014. The current activities of the high energy theory group in the Department cover aspects of black hole physics, quantum gravity, dark energy, physics beyond the Standard Model, high energy collider physics, particle cosmology and astrophysics, and non-commutative geometry. Expected research areas of the successful candidate may include any of a variety of topics in theoretical elementary particle physics such as physics beyond the Standard Model, applications of particle physics to cosmology and particle astrophysics, quantum gravity, and string theory. The new faculty member would benefit from interaction with the existing experimental groups in the Department: high energy physics at the Large Hadron Collider (CMS), neutrino physics (Double Chooz, EXO, KamLAND, MiniBooNE, LBNE), dark matter search (LZ), and astroparticle physics (IceCube, HAWC). More information about the department can be found on the departmental website, physics.ua.edu. The minimum qualifications for this position are a Ph.D. or equivalent, postdoctoral experience and scholarly publications. Candidates for this position are expected to have an outstanding research record and exhibit potential for effective teaching at the undergraduate and graduate levels. The successful candidate is expected to develop a high quality, externally funded research program, as well as teach and mentor at the undergraduate and graduate levels. To apply, go to facultyjobs.ua.edu/postings/34303 and complete the online application. Attach a letter of application, curriculum vitae with publication list, a summary of research plans, and a statement of teaching philosophy, as well as contact information for at least 3 references (names, telephone numbers, email and postal addresses). Arrange for letters from the references to be sent to the **Chair, Theoretical Elementary Particle Physics Search Committee, Department of Physics and Astronomy, Box 870324, The University of Alabama, Tuscaloosa, AL 35487** or sent electronically to okadan@ua.edu. For additional information, contact the search committee chair, **Dr. Nobuchika Okada**, at okadan@ua.edu or **+1 (205) 348-2837**. The review process will begin **December 01, 2013** and continue until the position is filled. *The University of Alabama is an Equal Opportunity/Affirmative Action Employer, and actively seeks diversity among its employees. Women and minorities are encouraged to apply.* C1113048

EXPERIMENTAL AMO PHYSICS FACULTY POSITION

The Department of Physics, Colorado State University, seeks to hire a tenure-track faculty member at the rank of Assistant Professor in experimental atomic, molecular, and optical physics. Exceptional candidates from all areas of AMO physics are encouraged to apply. Candidates must hold a Ph.D. in physics or an equivalent degree and have a documented potential for truly outstanding teaching, scholarship, and research. Postdoctoral and/or other substantial experience beyond the Ph.D. is expected. Complete applications must include a detailed CV, descriptions of research plans and teaching interests, and at least three letters of reference. Applications should be submitted online. For more information, including application instructions, see http://cns.natsci.colostate.edu/employment/Physics/. Applications completed by **December 15, 2013** will receive full consideration, but applications will be accepted until the position is filled. *Colorado State University is an EO/EA/AA employer and will conduct background checks on all final candidates.* C1113045

Faculty Position
Experimental Condensed Matter Physics
Columbia University

The Columbia University Department of Physics seeks to increase its strengths in condensed matter physics and nanoscience. In the first phase of our program we seek to hire a scientist active in experimental research and teaching in these or related areas at the rank of tenured associate or tenured full professor. We encourage applications from candidates with an outstanding record of research who will take a leadership role in a premier program, further developing our tradition of scientific accomplishment and interdisciplinary collaboration. Candidates are expected to have a doctoral degree in physics or a related field and a demonstrated record of outstanding research. Candidates should submit with their application a cover letter, Curriculum Vitae (including publication list), and brief statements of their research plans and teaching philosophy. Please visit our online application site at academicjobs.columbia.edu/applicants/Central?quickFind=58292 for further information about this position and to submit your application. Review of applications will begin immediately and continue until the position is filled. *Columbia University is an Equal Opportunity/ Affirmative Action employer. The department is especially interested in qualified candidates whose record of achievement will contribute to the diversity goals of the institution.* C1113050

Tenure-Track Assistant Professor in Experimental Condensed Matter Physics

The Department of Physics and Astronomy at **Stony Brook University** (http://www.physics.sunysb.edu/Physics/) seeks applications for a tenure track assistant professor in experimental condensed matter physics. The ideal candidate will bring skills and expertise that complement existing research in the department and will be able to form collaborative links to the condensed matter physics group and other groups in the department and university. The current interests of the condensed matter group can be found at http://mini.physics.sunysb.edu/~marivi/solidstate/ . Stony Brook faculty and students conduct experimental and theoretical research in a broad range of topics in physics and astronomy both in facilities on our campus and at laboratories around the world. The successful candidate will have a Ph.D. in Physics or in a related field. The candidate will be expected to build an experimental laboratory in the department and potentially make use of complementary user facilities at nearby Brookhaven National Laboratory. He or she will be expected to carry out an independent research program, and will contribute to the teaching activities in the department at both the undergraduate and graduate levels. The appointment could start as early as in Fall 2014. To receive full consideration the application should be submitted by **November 15, 2013**. Interested candidates should go to the web page https://academicjobsonline.org/ajo/StonyBrook/3167 and follow the links and instructions for uploading all application materials (including CV, a statement of teaching philosophy, a brief (3-page limit) description of research and research interests, and the names, institutions, and email addresses for 3 referees) to a secure web site. The letters of references should be submitted electronically on the same WEB site. Electronic submission via academicjobsonline is strongly preferred. Alternatively, applicants may submit the application materials by mail to: **Nathan Leoce-Schappin, Assistant to the Chair, P-104 Physics Bldg., Stony Brook, NY 11794-3800.** For a full position description and/or application procedures, visit www.stonybrook.edu/jobs (**Ref. # F-8178-13-09**). *Stony Brook University/SUNY is an equal opportunity, affirmative action employer.* C1113049

Tenure-Track Assistant Professor-Physics
College of Charleston

The Department of Physics and Astronomy (physics.cofc.edu) at the College of Charleston invites applications for a tenure-track assistant professor position in physics to begin in the fall of 2014. Candidates must have a commitment to excellence in teaching undergraduate physics courses at all levels. The incumbent must also establish and sustain a successful research program that involves undergraduate students, preferably in experimental condensed matter physics. Candidates who can interface with industry, and/or those who can help support and potentially expand the energy production concentration, are especially encouraged to apply. Candidates must have, or expect to complete, a PhD in physics or a closely related field before August 15, 2014. Post-doctoral experience is preferred. The College of Charleston is a public liberal arts and sciences college with approximately 10,000 undergraduates and 1,500 graduate students. The department currently has 17 faculty members and offers degrees in physics, astronomy, and astrophysics. Qualified applicants should submit 1) a complete curriculum vitae, 2) a statement describing their teaching experience and philosophy, 3) a description of their research background and plans, and 4) the names, addresses, e-mail addresses, and telephone numbers of three professional references electronically through our online application system at https://jobs.cofc.edu/. Any questions should be directed to the search committee chair, **Dr. Sorinel Oprisan**, at oprisans@cofc.edu. Review of applications will begin on December 1, 2013 and will continue until the position is filled. *The College of Charleston is an Affirmative Action/Equal Opportunity Employer. Women, underrepresented minorities and individuals with disabilities are encouraged to apply.* 1954781

Department of Electrical and Systems Engineering

Penn Engineering

Tenured/Tenure-Track Faculty Position

The Department of Electrical and Systems Engineering of the School of Engineering and Applied Science at the University of Pennsylvania invites applications for tenured and tenure-track faculty positions at all levels. Candidates must hold a Ph.D. in Electrical Engineering, Systems Engineering, or related area. The department seeks individuals with exceptional promise for, or proven record of, research achievement, who will take a position of international leadership in defining their field of study, and excel in undergraduate and graduate education. Leadership in cross-disciplinary and multi-disciplinary collaborations is of particular interest. We are interested in candidates in all areas that enhance our research strengths in

1. Nanodevices and nanosystems (nanophotonics, nanoelectronics, integrated devices and systems at nanoscale),
2. Circuits and computer engineering (analog and digital circuits, emerging circuit design, computer engineering, embedded systems), and
3. Information and decision systems (communications, control, signal processing, network science, markets and social systems).

Prospective candidates in all areas are strongly encouraged to address large scale societal problems in energy, transportation, health, economic and financial networks, critical infrastructure, and national security. Diversity candidates are strongly encouraged to apply. Interested persons should submit an online application at http://facultysearches.provost.upenn.edu/postings/40 including curriculum vitae, statements of research and teaching interests, and the names of at least four references.
Review of applications will begin on December 1, 2013.

The University of Pennsylvania is an Equal Opportunity Employer.
Minorities/Women/Individuals with Disabilities/Veterans are encouraged to apply.

Worcester Polytechnic Institute

Assistant Professor Physics

The Department of Physics invites applications for a junior level tenure-track position in experimental or applied optics to begin in the fall of 2014.

The successful candidate can or should be able to produce a vigorous externally funded research program, which would interact in the areas of soft-matter, biophysics, or nanoscience.

Position Requirements: Ph.D. in physics or in closely related area Experience in mentoring and teaching graduate and/or undergraduate students in a robust and collaborative research program, so as to participate effectively in WPI's distinctive curriculum, will be valued. Preference will be given to applicants who can complement the outstanding team of researchers present both in the department and at WPI.

Please see www.wpi.edu/research, www.wpi.edu/+Physics and www.gatewayparkworcester.com for current research interests and activities at WPI.

Closing Date: 12/01/2013

To apply, please visit: **http://apptrkr.com/398703**

WPI

To enrich education through diversity, WPI is an Affirmative Action, Equal Opportunity Employer.

Massachusetts Institute of Technology

Come work with us!

The Physics Department of the Massachusetts Institute of Technology invites applications for the faculty positions described below. Faculty members at MIT conduct research, teach undergraduate and graduate physics courses, and supervise graduate and undergraduate participation in research. Candidates must show promise in teaching as well as in research. Preference will be given to applicants at the Assistant Professor level.

The application deadline for all faculty positions is November 22, 2013. Applicants should submit a curriculum vitae, a list of publications, and a brief description of research interests and goals (the latter NOT TO EXCEED 3 PAGES IN LENGTH) at the following web site: http://www.academicjobsonline.com. Applicants should also arrange for three letters of reference to be uploaded to the same site. Only web submissions will be accepted.

Candidates who are uncertain whether they fit into a particular search should contact the most relevant search chair.

Astrophysics – The Astrophysics search is unrestricted with respect to area of specialization. Current astrophysics faculty are active in broad areas of observational astronomy and theoretical astrophysics, including optical/IR and high energy astronomy, studies of exoplanets, gravitational-wave science, and observational and theoretical cosmology. MIT hosts the Kavli Institute for Astrophysics and Space Research, whose faculty and research staff contribute instrumentation for and conduct research using several facilities including LIGO, the Magellan telescopes, the Chandra X-ray Observatory, the Murchison Widefield Array, and the Suzaku X-ray mission, as well as an in-house high performance computing cluster. Inquiries should be directed to Prof. Scott Hughes, Search Committee Chair, sahughes@mit.edu.

Biophysics/Soft Condensed Matter – We invite applications for a faculty position in the fields of Biological and Soft Condensed Matter physics. Preference is given to individuals working in experimental fields. Any inquiries should be directed to Professor Mehran Kardar, Search Committee Chair, kardar@mit.edu.

Hard Condensed Matter – The search in Experimental Condensed Matter Physics covers broad areas such as strong correlations, nanoscience, and quantum information. A wide range of experimental expertise will be considered. Any inquiries should be directed to Professor Raymond Ashoori, Search Committee Chair, ashoori@mit.edu.

Experimental Nuclear and Particle Physics – Currently, the research groups in the Nuclear and Particle Division and Laboratory for Nuclear Science have a wide range of interests in strong interaction physics (Jefferson Lab, OLYMPUS/DESY, CMS heavy ions), electroweak symmetry breaking (CMS), dark matter searches (CMS, AMS, DarkLight, DMTPC and MiniCLEAN), neutrino physics (KATRIN, Double Chooz, Daedalus, LBNE, and MicroBooNE) and physics beyond the standard model (CMS, LHCb, nEDM). This faculty search is broad in scope so that applicants with research interests in other areas of nuclear and particle physics are strongly encouraged to apply. Any inquiries should be directed to Professor Gunther Roland, Search Committee Chair, rolandg@mit.edu.

Theoretical Physics – The Center for Theoretical Physics is seeking applications in all areas of its activities with the purpose of making a junior faculty appointment. We particularly encourage applications in string theory and related areas of research, including quantum gravity, cosmology, black-hole physics, holography, supersymmetric quantum field theory, and mathematical physics. Candidates will be evaluated on the basis of potential contribution to both the research programs carried out in the Center for Theoretical Physics and to the undergraduate and graduate teaching programs of the Department of Physics. Current faculty in the Center for Theoretical Physics span a broad range of interests, including QCD, electroweak physics, unification, cosmology, string theory, and quantum computation. Any inquiries should be directed to Professor Barton Zwiebach, Search Committee Chair, zwiebach@mit.edu.

MIT is an Affirmative Action/Equal Opportunity employer committed to diversity and inclusion.

http://web.mit.edu

Openings of Tenure-Track and Research Faculty Positions at Tsinghua University
The Center for Quantum Information (CQI) within the Institute for interdisciplinary Information Sciences (IIIS), headed by the world-famous computer scientist and the Turing Award laureate, Prof. Andrew Chi-Chih Yao at Tsinghua University aims to build a world-class research and education center for Quantum Information and Interdisciplinary Sciences. CQI adopts the management method of top western institutions and provides excellent support for young researchers. CQI currently invites applications for Tenure-Track and Research Faculty positions. The interested areas include all directions of quantum information science. People with backgrounds in experimental physics are particularly encouraged to apply. The remuneration package will be very attractive, driven by market competitiveness and individual qualification. CQI will also support the qualified applicants to apply for the Chinese National Recruitment program the "Youth 1000-Talents" fellowship. Further information is available at http://iiis.tsinghua.edu.cn/en/. Interested applicants should send a detailed curriculum vita with a publication list, a teaching and research statement, names and contact addresses of 3 to 5 people who can provide reference letters, by email to the following address: iiisrecruit@mail.tsinghua.edu.cn with the subject line"<candidate_name>: CQI Faculty Application". C1113044

Faculty Position Experimental AMO at Georgia Tech
Georgia Institute of Technology
Faculty Position in Experimental Atomic, Molecular and Optics School of Physics Georgia Institute of Technology The School of Physics of the Georgia Institute of Technology invites applications for a faculty position in experimental atomic, molecular and optics physics beginning Fall 2014. We are especially interested in candidates in cold atoms, molecules and ions, quantum optics, quantum information, and ultra-fast optical physics. Applicants at the assistant, associate, and full professor levels are encouraged to apply. Successful applicants are expected to direct an active program of funded research and to teach effectively at both the undergraduate and graduate levels. Applicants should email to amo.search@physics.gatech.edu the following documents in PDF format: 1) cover letter, 2) curriculum vitae including a full list of publications and relevant teaching experience, 3) a research plan for the next five years (maximum 3 pages), and 4) a statement of teaching philosophy and experience (maximum 1 page). In addition, junior applicants should arrange to have three letters of reference emailed separately to the same address. Review of applications will begin **December 1, 2013**. *Georgia Tech is a unit of the University System of Georgia and an equal education/employment opportunity institution.* 1943655

POSTDOCTORAL POSITIONS IN CONDENSED MATTER THEORY
University of Tennessee at Knoxville
Postdoctoral positions in Condensed Matter Theory are available at the Department of Physics of the University of Tennessee, Knoxville, in the group of Profs. Elbio Dagotto and Adriana Moreo. Areas of interest are iron and copper based high critical temperature superconductors, non-equilibrium properties of correlated electronic systems, oxide interfaces, bulk complex oxides, multiferroic materials, transport in nanostructures, and others. We use a variety of many-body techniques, mainly computational. Information about our group can be found in http://sces.phys.utk.edu The main location for this work will be the University of Tennessee, but our group has a close connection with Oak Ridge National Laboratory where part of the postdoctoral effort could be performed. Candidates should submit electronically their application, CV, and statement of research interests (in asingle file) to both: (1) applications@sces.phys.utk.edu via email, and (2) https://ut.taleo.net/careersection/ut_knoxville/jobdetail.ftl?lang=en&job= 13000000YR via online application. The (three) letters of recommendation, and any question about the available positions, should be submitted via email to applications@sces.phys.utk.edu only. Screening of applicants will start immediately until the position is filled. 1954797

Tenured Full Professor Position at Temple University
The Physics Department at **Temple University** invites applications for a full-time faculty position at the tenured professor level with a start date of September 2014. Preference will be given to the area of experimental materials physics, while outstanding candidates in other areas, such as nuclear physics, computational physics, and atomic-molecular optical physics, may also be considered. Applicants must have a Ph.D. in physics or closely related areas and a demonstrated record for excellence in teaching and research, including research funding. The successful candidate is expected to establish an outstanding research program, and actively participate in the educational programs and other activities of the department. To apply please send a curriculum vitae, publication list, research plan, research funding history, statement of teaching philosophy, and arrange to have five letters of recommendation all on-line: https://phys.cst.temple.edu/. Application deadline is **January 31, 2014**. However, the search will remain open until the position is filled. *Temple University is exceedingly diverse in all aspects of University life and is an Equal Opportunity/Affirmative Action Employer.* C1113034

Postdoctoral Research Associate - Unconventional Superconductivity
Ames Laboratory/Iowa State University
The Superconductivity and Magnetism Low-Temperature Laboratory (http://www.cmpgroup.ameslab.gov/supermaglab), part of US DOE Ames Laboratory, invites applications for a postdoctoral research position to study electromagnetic and thermodynamic properties of unconventional superconductors. The project involves high–resolution measurements of the magnetic penetration depth under pressure as well as thermal and electric conductivities in a dilution refrigerator and various 3He and 4He cryostats. Ph.D in physics or related field is required. The successful candidate must be supported by peer–reviewed publications, demonstrate practical knowledge of low-temperature (< 1 K) experiments, hands-on experience with laboratory electronics, cryogenics, vacuum systems, LabView programming as well as experience in data processing and modeling, including AutoCAD, Matlab, Mathematica, Origin, or similar programs. To apply, send a CV, a list of publications, names of three references, and a statement of research experience to **Prof. Ruslan Prozorov** by e-mail at prozorov@ameslab.gov. *Ames Laboratory/Iowa State University is an Affirmative Action/Equal Opportunity Employer.* 1954877

Assistant Professor of Physics
Missouri University of Science & Technology
Missouri University of Science & Technology Tenure Track Faculty Position Experimental Condensed Matter Physics The Physics Department at Missouri University of Science & Technology (Missouri S&T) invites applications for a tenure track faculty position at the Assistant Professor level in the area of experimental condensed matter physics to begin in August 2014. Particular consideration will be given to candidates working in areas that complement existing experimental and theoretical research programs. The successful candidate must have a Ph.D. in Physics or an equivalent degree and have demonstrated outstanding research accomplishments, a commitment to excellence in teaching at all levels, and excellent communications skills. More information is available at http://physics.mst.edu. Applications, including curriculum vitae, complete publications list, at least three letters of recommendation, a brief description of research interests, and a statement of teaching philosophy should be submitted electronically to the Missouri University of Science and Technology's Human Resource Office at http://hraadi.mst.edu/hr/employment/. All submitted application materials must include the position reference number **00030865** in order to be processed. Acceptable electronic formats that can be used for email attachments include PDF and Word; hardcopy application materials will not be accepted. Applications will be considered until the position is filled; review of applications will begin **Jan. 1, 2014**. The final candidate is required to provide official transcript(s) for any college degree(s) listed in application materials submitted. Copies of transcript(s) must be provided prior to the start of employment. In addition, the final candidate may be required to verify other credentials listed in application materials. Failure to provide official transcript(s) or other required verification may result in the withdrawal of the job offer. *Missouri S&T is an AA/EO Employer and does not discriminate based on race, color, religion, sex, sexual orientation, national origin, age, disability, or status as Vietnam-era veteran. Females, minorities, and persons with disabilities are encouraged to apply. Missouri S&T is responsive to the needs of dual-career couples. Missouri S&T participates in E-Verify. For more information on E-Verify, please contact DHS at 1-888-464-4218.* 1955274

Assistant Professor, Experimental Condensed Matter Physics
North Dakota State University
The Department of Physics at North Dakota State University invites applications for a tenure-track faculty position at the Assistant Professor level in experimental condensed matter physics, targeting research expertise in experimental soft matter, nanotechnology, biological physics, or polymer physics. We seek an outstanding candidate who is able to establish a highly visible research program and develop collaborations within the department and across the university. Minimum qualifications include a Ph.D. in physics or a related field, potential to attract external funding, ability to teach undergraduate and graduate courses, and effective communications skills. Postdoctoral experience is preferred. Applicants should submit a vita, research plan, teaching philosophy, and contact information for three references at https://jobs.ndsu.edu/postings/4111. Review of applications will begin **January 6, 2014**. *North Dakota State University is an Equal Opportunity/Affirmative Action Employer.* C1113054

The Department of Physics at the **University of Wisconsin - Madison** invites applications for an **assistant professor (tenure-track) position**. Applicants in all areas of physics will be considered, with special emphasis on cosmic frontier experimentalists and on theorists and experimentalists in condensed matter physics, biophysics, and quantum optics. Undergraduate and graduate classroom and individual instruction as well as supervision of graduate thesis research are required. Ph.D. required before start of appointment. Candidates should apply with a CV, publications list, research statement, teaching statement, and at least 3 letters of reference at: http://www.physics.wisc.edu/apply/pvl_77776/ (Paper Submissions are strongly discouraged.) To ensure consideration please submit application materials by **December 1, 2013**. *The University of Wisconsin–Madison is an equal opportunity/affirmative action employer, and especially encourages women and underrepresented minorities to apply. Unless confidentiality is requested in writing, information regarding the applicants must be released upon request. Finalists cannot be guaranteed confidentiality. A criminal background check will be required prior to employment.* For further information email info@physics.wisc.edu. University of Wisconsin-Madison Position Vacancy Listing PVL# 77776. C1113059

Tenure Track Assistant/Associate/Full Professor
Department of Physics/University of Miami
The Department of Physics at the University of Miami invites applications from highly qualified persons for a faculty position in the experimental study of dynamical processes underlying brain function, including the collective firing of neurons. An appointment will be made at the Assistant or Associate Professor rank, or at the Full Professor level for exceptional candidates, starting fall 2014. Researchers using state-of-the-art or novel sensing and imaging techniques are strongly encouraged to apply. The successful candidate will interact with existing experimental and theoretical physics faculty and join the University's new brain research initiative that includes an fMRI facility and molecular-level research on individual neurons. Candidates must have a Ph.D. in physics or a related field, a demonstrated record of research achievements, and a strong commitment to teaching and mentoring students at the undergraduate and graduate levels. The Physics Department is located within the University's attractive Coral Gables campus in the greater Miami area, and has a wide-ranging research expertise and established Ph.D. program. Application materials, including curriculum vitae with list of publications and statement of research plans, should be sent electronically (as a single PDF) to brainsearch@physics.miami.edu or to **Brain Search Committee Chair, Department of Physics, University of Miami, Knight Physics Building, Coral Gables, Fl. 33124.** Applicants should arrange for three letters of recommendation to be sent to the same address. Review of applications will begin on **December 2, 2013** and continue until the position is filled. *The University of Miami is an equal opportunity/affirmative action employer that values diversity and has progressive work-life policies. Women, persons with disabilities, and members of other underrepresented groups are encouraged to apply.* 1955659

Department Chair and Full Professor

The Physics Department at **Marquette University** invites applications for a Department Chair/Full professor with tenure to begin July 1, 2014. The department offers a Bachelor of Science degree in Physics, and is seeking candidates with a Ph.D. in physics or related field, scholarly record to warrant appointment as a Full Professor with tenure, demonstrated excellence in teaching physics, an active research program, administrative experience, and strong interpersonal skills. Applicants must have a strong interest in undergraduate teaching and engaging undergraduate students in research. Teaching responsibilities include teaching introductory and upper level courses offered by the Department. Please apply to this position at http://employment.marquette.edu/postings/2119. For more information about the physics department, please go to www.mu.edu/physics. C1113084

Tenure-track Assistant Professor of Physics
California State University San Marcos

California State University San Marcos has an opening for a tenure track assistant professor of physics to begin August 2014. Candidates must have a Ph.D. in physics, applied physics, or a closely related field. Successful candidates will have a demonstrated commitment to excellence in undergraduate teaching and be able to develop a research program that involves undergraduates. The preferred research area is biological physics or a related area such as medical physics, applied optics, acoustics, or soft condensed matter; however exceptional candidates in other research specialties will be considered. An interest in teaching undergraduate electronics courses is desirable. Preference will be given to applicants with demonstrated intercultural competence with diverse groups in teaching, research and/or service. The position is at the assistant professor level; however, under exceceptional circumstances applicants at the untenured associate level may be considered. Applicants should submit a curriculum vitae, a one-page statement of teaching philosophy, a one-page statement of future research plans, and a completed Faculty Application; and arrange for three letters of reference. Materials should be sent to: **Physics Search Committee,** PHYSTT@csusm.edu. To assure full consideration, all application materials should be received on or before **1/13/2014**. However, applications will be accepted until a suitable candidate is found. For more information and faculty application form, please visit http://www.csusm.edu/facultyopportunities. C1113087

KOREA INSTITUTE FOR ADVANCED STUDY (KIAS)
Postdoctoral Research Fellow and KIAS Assistant Professor in Theoretical Physics

The School of Physics at Korea Institute for Advanced Study (KIAS) invites applicants for the positions of Postdoctoral Research Fellow and KIAS Assistant Professor in theoretical physics. Applicants are expected to have demonstrated remarkable research potential, including major contributions beyond or through the doctoral dissertation. For research fellows, annual salary starts from 42,000,000 Korean Won (approximately US$39,000 at current exchange rate) and additional research funds of 10,000,000 Korean Won (US$9,300) will be provided each year. The initial appointment for the position is for two years and is renewable for up to two years, depending on your research performance and the needs of the research program at KIAS. Exceptional candidates may be asked to join KIAS as KIAS Assistant Professors. Annual salary for the position starts from 50,000,000 Korean Won (US$46,000) and research funds of 15,000,000 Korean Won (US$14,000) will be provided per year. The initial appointment is for two years and is renewable for up to three additional years. The deadline is December 29 for positions beginning in Spring 2014 or earlier. Applications must include a complete vitae with a cover letter, a list of publications, and a research plan. Three letters of recommendation should be mailed to: **Ms. Sunmi Wee, Korea Institute for Advanced Study (KIAS), 85 Hoegiro (Cheongnyangni-dong 207-43), Dongdaemun-gu, Seoul 130-722, Republic of Korea.** Those interested are encouraged to contact individual faculty members. Visit our website at http://www.kias.re.kr to learn about our faculty members and their research interests. You can also submit your application materials at AcademicJobsOnline. 1961624

PHYSICS DEPARTMENT, TENURE TRACK FACULTY POSITIONS. The Physics Department invites applications for full-time, academic year, tenure-track positions at **California Polytechnic State University, San Luis Obispo, CA,** beginning 9/15/2014. Rank and salary to be commensurate with qualifications and experience. Primary duties and responsibilities are to teach undergraduate physics or astronomy and to maintain an active professional development program that provides research experiences for undergraduate students. A Ph.D. in physics or related field is required and must be completed prior to start of appointment. Must provide evidence of (or potential for) high quality teaching. Applicants in fields that complement the existing research activities in the department and interdisciplinary programs at Cal Poly are encouraged to apply. For details, qualifications, and application instructions (online application required), visit WWW.CALPOLYJOBS.ORG and apply to **Requisition #103025**. Review Begin Date: **December 2, 2013**. *EEO.* C1113088

Postdoctoral Scholars
Wisconsin IceCube Particle Astrophysics Center (WIPAC) at UW-Madison

WIPAC (the Wisconsin IceCube Particle Astrophysics Center, at the University of Wisconsin, Madison) is hiring two postdoctoral scholars in astro-particle physics to work on the IceCube observatory and/or the Cherenkov Telescope Array. Applicants must have (or soon have) a PhD in experimental astro-particle physics or a closely related field. Experience with hardware (in particular electronics), Monte Carlo simulations, and analysis of astro-particle data is preferred. Each position is for two years, with the possibility of an additional year contingent on performance and funding. IceCube has recently discovered astrophysical neutrinos in the 100 TeV to 1 PeV energy range, and further data taking and analysis are underway. CTA groups in the US are building an innovative dual-mirror Cherenkov telescope that will be installed in Arizona. UW Madison has strong physics and astronomy departments, and WIPAC is a particularly active center for astro-particle research. Madison is the lead institution for IceCube and plays important roles in HAWC, the Askaryan Radio Array, DM-Ice, and CTA. WIPAC has a strong group of theorists who work with the experimentalists. Send a CV, publication list, and statement of research interests to postdoc@wipac.wisc.edu. Arrange for three letters of recommendation to be sent to the same address. Send inquiries to **Prof. Justin Vandenbroucke**, vandenbrouck@wisc.edu or **Prof. Albrecht Karle**, albrecht.karle@icecube.wisc.edu. Review of applications will begin **December 16, 2013** and continue until the positions are filled. 1960913

ASSISTANT PROFESSORS OF PHYSICS, UNIVERSITY AT ALBANY, SUNY

The Physics Department at the University at Albany, State University of New York, invites applications for two tenure-track faculty positions starting in Fall 2014.

Assistant Professor in Particle Astrophysics and Cosmology

We seek an outstanding experimentalist or theorist with significant accomplishments who will benefit from the vigorous experimental and theoretical particle physics programs in the Physics Department.

Assistant Professor in Experimental Imaging/Spectroscopic and Computational Physics

We seek outstanding applicants with expertise in spectroscopic or imaging physics, with a preferred focus in computational/Bayesian/Information-theoretic methods. Desirable candidates will be able to collaborate with existing programs in physics, such as EPR, x-ray optics, robotics, astrophysics, or at the university, such as the RNA Institute, computational and chemical forensics, big data, genomics, and the Wadsworth Laboratory of the NYS Department of Health. Requirements for both positions include a Ph.D. in Physics or related field and demonstrated scholarly productivity. Successful candidates will be committed to excellence in teaching at all levels and expected to develop a vigorous and externally funded research program. Applicants should submit a letter of application, vitae, and statement of research plans online (see http://jobs.physicstoday.org/jobs/5766056) and must address in their application their ability to work with and instruct a culturally diverse population. Please arrange to have at least three letters of reference sent directly to the department. Inquiries, applications, and letters of reference may be addressed to physics@albany.edu, or **Physics Search, University at Albany, 1400 Washington Ave., Albany, New York 12222.** Review of applications will begin on **December 1, 2013** and continue until the position is filled.

THE UNIVERSITY AT ALBANY IS AN EO/AA/IRCA/ADA EMPLOYER.
We have a strong commitment to the affirmation of diversity. C1113095

Tenure Track Assistant Professor of Physics

Kettering University's Physics program is built on experiential education with an emphasis on work integrated and active learning, implemented by alternating academic and co-op or experiential education terms. We offer two ABET accredited bachelor degrees, Applied Physics and Engineering Physics, as well as five minors in Physics, Optics, Acoustics, Materials Science, and Medical Physics. A PhD in Physics or a closely related field is required. Preferred areas of expertise will augment current departmental strengths in condensed matter, and may complement interests in medical physics or biological applications. The establishment of a new Applied Biology program at Kettering University and a new Proton Beam Therapy center at nearby McLaren Hospital provide excellent collaborative opportunities. We are committed to a teacher-scholar model with a focus on student learning, intellectual and professional growth, and career success. The successful applicant is expected to establish an active and collaborative research program that improves department capabilities, supports professional development of faculty, and enhances opportunities for student learning. Preferred start date for this position is July 2014. Applications completed before **December 1, 2013** will receive full consideration. Apply for this position on-line at https://jobs.kettering.edu. *AA/EOE.* C1113085

TENURE –TRACK POSITION FOR EXPERIMENTAL PHYSICIST AT BENEDICTINE COLLEGE

The Physics & Astronomy Department of Benedictine College is seeking an experimental physicist with a strong commitment to teaching and research. PhD required. Benedictine College is a Catholic, liberal arts residential college whose mission is the education of men and women within a community of faith and scholarship. Preferential consideration will be given to applicants in condensed matter physics or related fields who can establish an active research program involving undergraduates. For a full description and application instructions, see http://www.benedictine.edu/physics-faculty. Review of applicants will begin **December 10, 2013**. C1113086

Experimental Condensed Matter/Surface/Nanoscale Physics Faculty Position
University of Central Florida

The Department of Physics (physics.cos.ucf.edu) at the University of Central Florida invites applications for a tenure-track position at the Assistant Professor level or higher beginning in August 2014. We seek candidates with research experience in experimental Condensed Matter Physics, particularly with emphasis on Surface and/or Nanoscale Physics. Applicants must have a Ph.D. in Physics, or a related discipline, and a substantial record of independent, well regarded research. The successful applicant is expected to establish a vigorous, externally funded research program and have a strong commitment to excellence in graduate and undergraduate education. UCF is a leading, fast growing, metropolitan research university with about 60,000 students. The Department of Physics currently has 40 faculty members, offers B.S., M.S., and Ph.D. degrees, and has recently moved into a state-of-the-art research building. Research programs include condensed matter physics, surface physics, nanoscience, soft condensed matter, planetary science, biological physics, atomic and optical physics, attosecond physics, quantum information processing, and physics education. There are opportunities to benefit from a synergy with the Nanoscience and Technology Center, the Advanced Materials Processing and Analysis Center (AMPAC), the College of Optics and Photonics (CREOL), the Biomolecular Sciences Center, and the College of Medicine. Interested individuals must complete an on-line application by going to: jobswithucf.com. The online application should include a cover letter, curriculum vitae, summary of research and teaching portfolio, and a list of three references with contact information. Screening of applications will begin **November 15, 2013** and will continue until the position is filled. *The University of Central Florida is an Affirmative Action/Equal Opportunity Employer. Minorities and women are encouraged to apply. The Physics Department is female friendly, with a female chair, an active Women in Physics Group, and a strong commitment to enhance diversity. As an agency of the State of Florida, UCF makes all application materials and selection procedures available for public review upon request.* C113089

Tenure Track Assistant Professor in Astronomy/Astrophysics at Texas Christian University

The Department of Physics and Astronomy at Texas Christian University invites applications for a tenure-track faculty position in the area of Astronomy or Astrophysics at the Assistant Professor level to begin in Fall 2014. The successful candidate will be expected to teach undergraduate and graduate courses in astronomy and physics, advise PhD candidates, and conduct an independent and vigorous research program. We expect that the new faculty member will strengthen and expand our undergraduate and graduate programs in astronomy/astrophysics. The departmental focus in astronomy/astrophysics is currently observational Galactic astronomy, with an associate membership in the Sloan Digital Sky Survey III and IV. Applicants should have a PhD in Astronomy, Astrophysics, or Physics, a strong record of achievement in astronomy or astrophysics related research, and a commitment to excellence in undergraduate and graduate teaching and outreach. Other important assets include post-doctoral experience and a research plan capable of attracting external funding. The Department has an active student body with close faculty student interactions and a history of success in obtaining funding from NSF and other external sources. For further information about the Department see http://www.phys.tcu.edu. Applications must include a cover letter, curriculum vitae, a list of publications, a research statement, a statement on teaching philosophy, and complete contact information for at least three professional references. Applications must be submitted through the TCU Human Resources website at https://tcu.igreentree.com/CSS_Faculty. The review of applications will begin **February 1, 2014** and continue until the position is filled. *TCU is an equal opportunity employer.* C1113061

The Department of Physics at **Gettysburg College** invites applications for a tenure-track position in experimental physics at the **Assistant Professor** level, to begin August 2014. Responsibilities include teaching courses across the undergraduate physics curriculum (including advanced lab courses), conducting a dynamic research program involving undergraduates, and actively participating in the governance of the department and college. The successful candidate will also have opportunities to teach in the broader college curriculum through interdisciplinary courses and our First-Year Seminar program. We seek an individual who has a genuine interest in teaching, advising, and scholarship within the liberal arts. Candidates must have a doctorate in physics (or closely allied field); preference will be given to experimentalists who represent the broad arena of applied physics and will establish an on-campus research lab. Postdoctoral research experience and college-level teaching experience are preferred. Please visit our website to submit your electronic application: https://gettysburg.peopleadmin.com/postings/761 including a cover letter, curriculum vitae, a statement of current and future research plans (under the portfolio section of the on-line application), and a statement of teaching philosophy and experience. Please limit the CV to 4 pages and each statement to 3 pages. Professional references will be contacted by Gettysburg College to submit letters of recommendation electronically. Applications received by **December 1st** will be given fullest consideration, but submissions will continue to be reviewed until the position is filled. Letters of recommendation should be submitted by **December 11th**. Inquiries can be addressed to **Dr. Jacquelynne Milingo** at jmilingo@gettysburg.edu. *Gettysburg College is a highly selective liberal arts college located within 90 minutes of the Baltimore/Washington metropolitan area. Established in 1832, the College has a rich history and is situated on a 220-acre campus with an enrollment of over 2,600 students. Gettysburg College celebrates diversity and welcomes applications from members of any group that has been historically underrepresented in the American academy. The College assures equal employment opportunity and prohibits discrimination on the basis of race, color, national origin, gender, religion, sexual orientation, gender identity, gender expression, age, and disability.* C1113062

Physics, Assistant Professor (2 Tenure-track positions)
University of Nebraska Kearney

Physics, Assistant Professor (2 Tenure-track positions), The Department of Physics & Physical Science at the University of Nebraska at Kearney invites applications for two tenure-track positions to begin in August, 2014. For more information and to apply visit http://unkemployment.unk.edu. Direct questions about the position to: **Lee Powell, Search Committee Chair, Department of Physics and Physical Science, University of Nebraska at Kearney, Kearney, NE 68849** E-mail: powellwl@unk.edu Direct questions about the application process to: **(308) 865-8655** or employment@unk.edu. *AA/EO/ADA* www.unk.edu. 1958419

Faculty Position in Astrophysics with focus on Star and Planet Formation
Rice University

The Department of Physics and Astronomy at Rice University invites applications for a tenure-track faculty position in astrophysics with an emphasis on the formation of stars and planets within the Milky Way and in the low-redshift universe. This search seeks an outstanding individual whose research will complement and extend existing activities in star and planet formation at Rice University (see http://physics.rice.edu/). While some preference will be given to observational astrophysicists, outstanding candidates with a theoretical or computational focus will also receive full consideration. In addition to developing an independent and vigorous research program, the successful applicant will normally be expected to teach one undergraduate or graduate course each semester. The department expects to make an appointment at the assistant professor level. A PhD in astronomy/astrophysics or related field is required. Applicants should send a curriculum vitae, statements of research and teaching interests, a list of publications, and two or three selected reprints, in a single PDF file, to umbe@rice.edu with subject line "Astrophysicist Search" or to **Prof. Hartigan, Chair, Search Committee, Dept. of Physics and Astronomy – MS 61, Rice University, 6100 Main Street, Houston, TX 77005.** Applicants should also arrange for at least three letters of recommendation to be sent by email or post. Applications will be accepted until the position is filled, but only those received by **January 15, 2014** will be assured full consideration. The appointment is expected to start in July 2014. *Rice University is an affirmative action/equal opportunity employer; women and underrepresented minorities are strongly encouraged to apply.* C1113063

Postdoctoral Position in Computational Ultracold Plasma Physics

For research work on the **New Mexico Consortium** project "Computational and Theoretical Investigations of Ultra-Cold Plasmas," sponsored by Air Force Office of Scientific Research. Our team's efforts are directed toward the development, implementation, and application of advanced computational and algorithmic simulation methods for the study of ultracold plasmas (UCPs). UCPs are plasmas with exceptionally low temperatures, in the -450F range, making them one of the most exotic plasmas in the universe. The post doc will be involved in developed new methods in molecular dynamics simulations of such plasmas on advanced (GPU) architectures, and exploring various physical phenomena. Close collaborations with other groups, including experimental groups, are expected. **Qualifications:** A PhD in computational or theoretical physics, or a closely related field, completed within the last five years. The successful candidate will have a strong track record of creativity and publishing in top peer-reviewed journals. Apply online at www.newmexicoconsortium.org and attach CV/resume and cover letter. *EOE MFVD.* 3069

FACULTY POSITION
DEPARTMENT OF PHYSICS, UNIVERSITY OF ILLINOIS AT CHICAGO
MATERIALS SCIENCE DIVISION, ARGONNE NATIONAL LABORATORY

The University of Illinois at Chicago (UIC) and Argonne National Lab (ANL) invite applicants for a position in computational condensed matter and materials physics with emphasis on energy and nanoscience. This is an Assistant Professor position at UIC with an associated appointment at ANL, and we are envisioning individuals who will build a world class program that provides synergistic coupling between the two institutions. UIC is a Research I public university in the heart of Chicago and ANL is a leading national laboratory near Chicago. A more complete description of our programs can be found at www.msd.anl.gov and www.phy.uic.edu. The successful candidate must have a Ph.D. in a relevant area and postdoctoral experience. This is a tenure-track Assistant Professor level position; options for accelerated tenure consideration exist for outstanding candidates. For position details and to apply, please go to https://jobs.uic.edu/job-board/job-details?jobID=35698&job=assistant-professor-physics. Applications, which must include a CV, a statement of research interests, and the names of at least 3 references, must be completed by **December 20, 2013**. *UIC is the largest university in the Chicago area with 27,000 students, 15 colleges, including the nation's largest medical school, and one of the nation's most diverse student bodies. The University of Illinois is an Affirmative Action/Equal Opportunity Employer.* For additional information, please refer to UIC's Home Page at www.uic.edu. ANL is a multi-program laboratory managed by UChicago Argonne, LLC for the U.S. Department of Energy's Office of Science. *ANL is an equal opportunity employer and values diversity in their workforce.* Argonne's site is located about 25 miles southwest of Chicago on a beautiful 1500 acre campus. For additional information, please refer to Argonne's Home Page at www.anl.gov. C1113066

TEACHING ASSISTANT PROFESSORS
DEPARTMENT OF PHYSICS
NORTH CAROLINA STATE UNIVERSITY

Applications are invited for a full-time non-tenure-track Teaching Assistant Professor position in the NC State University Department of Physics beginning in the fall semester of 2014. The initial appointment is for three years with possible renewal and promotion in rank. In addition to teaching, responsibilities may include course administration for introductory physics, supervising laboratory sections, mentoring, recruiting and/or other roles shaped by the strengths and interests of the individual. Candidates must have a Ph.D. in physics or a physics-related area and a documented commitment to teaching excellence. Review of applications will begin immediately and will continue until the position is filled. To apply, please visit https://jobs.ncsu.edu and designate position number **00101204**. You will be required to send a curriculum vitae, a summary of administrative and teaching experience, teaching professional development activities and contact information for at least two references. The Department is particularly interested in candidates with records of successful teaching and management of large enrollment courses. *The College of Sciences welcomes the opportunity to work with candidates to identify suitable employment opportunities for spouses or partners. AA/EEO. In addition, NC State University welcomes all persons without regard to sexual orientation or genetic information. ADA Accommodations: contact 919-515-2135 or employment@ncsu.edu.* C1113073

Tenure-Track Assistant Professor Position in
Nucleon Decay and Neutrino Physics
Stony Brook University

The Department of Physics and Astronomy at Stony Brook University http://www.physics.sunysb.edu/Physics/ seeks to hire a tenure-track assistant professor in experimental nucleon decay and neutrino physics. It is expected that the appointment will begin in Fall 2014. Stony Brook faculty and students conduct experimental and theoretical research in a broad range of topics in physics and astronomy both in facilities on our campus and at laboratories around the world including the nearby Brookhaven National Laboratory. A successful candidate will have a Ph.D. degree in physics, and relevant postdoctoral experience and publications. S/he will be expected to carry out independent research program and to attract federal grant support for it. S/he will contribute to the teaching activities in the department at both the undergraduate and graduate levels. A joint appointment with Brookhaven National Laboratory may be possible. To receive full consideration the application should be submitted by **December 9, 2013**. Interested candidates should go to the web page https://academicjobsonline.org/ajo/jobs/3236 and follow the links and instructions for uploading all application materials (including CV, a statement of teaching philosophy, a brief (3-page limit) description of research and research interests, and the names, institutions, and email addresses for 5 referees) to a secure web site. The letters of references should be submitted electronically on the same WEB site. Electronic submission via academicjobsonline is strongly preferred. Alternatively, applicants may submit the application materials by mail to: **Nathan Leoce Schappin, Assistant to the Chair, P-104 Physics Bldg., Stony Brook, NY 11794-3800.** For a full position description and/or application procedures, visit www.stonybrook.edu/jobs (Ref. **# F-8202-13-10.**). *Stony Brook University/SUNY is an equal opportunity, affirmative action employer.* C1113064

13 experimental/theoretical PhD positions within the FP7 Marie Curie Initial Training Network: COMIQ
Cold Molecular Ions at the Quantum Limit
(EU Marie Curie Initial Training Network)

The aim of the COMIQ network is to investigate and control a variety of molecular ion processes at the very quantum limit. COMIQ will work on establishing cold molecular ions as new quantum objects for applications in quantum technology, precision measurements, and controlled chemistry. The network is highly interdisciplinary, combining quantum optics, quantum information sciences, molecular physics, and chemical physics in a novel and original fashion. The COMIQ network consists of ten partners, both academic and industrial. We therefore invite strong candidates from relevant disciplines to apply for an ESR fellowship. The fellowships are available from **November 1, 2013**. Links to the nodes and written descriptions of the projects are available at our website www.itn-comiq.eu. Any questions may be submitted to celia@phys.au.dk. Partners are: U Aarhus (DK), U Basel (CH), CNRS (LKB, LAC) (F), U Oxford (UK), U Düsseldorf (DE), U Ulm (DE), U Bonn (DE), HighFinesse (DE), Alpes Lasers (CH), Stahl Electronics (DE), U Innsbruck (AT). 1958266

Faculty and postdoctoral positions
School of Physics at Nanjing University, China

Faculty and postdoctoral positions School of Physics at Nanjing University, China The School of Physics at Nanjing University invites application for tenured/tenure-track faculty positions and postdoctoral positions in the fields of theoretical and experimental condensed matter physics, optics and photonics, acoustics, particle and nuclear physics, biophysics, soft matter physics, atomic and molecular physics, as well as computational physics. Positions and Qualifications We are seeking outstanding candidates for all levels of faculty positions, including tenured full/associate professors and tenure-track research professors. Candidates should have a Ph.D. in a relevant discipline and an exceptional record of research accomplishments. The individual's work experience and research achievements will determine the position offered. We are also seeking qualified candidates for postdoctoral position. Candidates should have a Ph.D. in a relevant discipline or expect a Ph.D. within one year, with demonstrated research potential. Salary and Benefits All newly hired tenured faculty members will be provided sufficient startup resources and necessary research infrastructures. Annual salaries for tenured full professors range from 400K to 800K RMB (equivalent to US$65,000-130,000). Annual salaries for tenured associate professors range from 250K to 350K RMB (equivalent to US$40,000-55,000). Generous housing package will also be offered. Annual salaries for tenure-track research professors and postdocs range from 80K to 200K RMB (equivalent to US$13,000-32,000). Rank and salary will be commensurate with work experience and research performance. Two-year initial contracts are renewable. Outstanding performers are invited to join in faculty. To apply Application materials include a cover letter, a full CV with the publication list, a statement of future research plans, and three letters of recommendation. Complete application packages and reference letters should be directed to **Miss Lan Cui** (Email: cuilan@nju.edu.cn; Tel: **+86 25 83594682**). 1959719

Physics – Tenure Track Assistant Professor
Misericordia University

Misericordia University invites qualified candidates to apply for a 10 month tenure-track faculty position in Physics to begin August 15, 2014. The three-person department primarily teaches introductory physics courses to students in a variety of majors. A doctorate in Physics, Physics Education, or a related field is required. Candidates at ABD status with evidence of expected completion by August 15, 2014, will be considered. Misericordia University is committed to student, faculty and staff diversity and values the educational benefit this brings to campus. Candidates should indicate any experience and/or leadership that contribute to this goal. To apply, please send a letter of application, curriculum vitae, a 1-2 page statement of teaching philosophy, transcripts, and three letters of reference by email to hr@misericordia.edu or by mail to **Office of Human Resources, Misericordia University, 301 Lake Street, Dallas, PA 18612.** Inquiries only should be directed to **Dr. Michael Orleski**, email: morleski@misericordia.edu. Dr. Orleski will be available at the January AAPT meeting in Orlando, FL by request for in-person inquiries. Review of applications will begin **January 15, 2014** and will continue until the position is filled. Misericordia University, an 89-year-old institution founded by the Sisters of Mercy, offering baccalaureate, master's, and doctoral degrees, is located adjacent to the Pocono Mountains region of Northeastern Pennsylvania, approximately 2 hours from New York City and Philadelphia. The university's approach of combining a quality liberal arts education with professional preparation and service to others has resulted in its wide regional acclaim. 1955075

Faculty Positions
Department of Physics, Applied Physics and Astronomy
State University of New York (SUNY) at Binghamton

Outstanding applicants are sought for two tenure track positions at the Assistant Professor level in the Physics Department at Binghamton University (in exceptional cases, a more senior appointment may be considered). The Department is seeking both a theoretical physicist and a computational physicist. Fields of interest are condensed matter physics, materials physics, and AMO physics. The successful candidates are expected to establish independent research programs, contribute effectively to our undergraduate and graduate teaching programs, and complement the energy-related interdisciplinary research programs at our university. A Ph. D. in Physics and postdoctoral experience are required. Applicants should submit a full curriculum vitae, statement of research interests, statement of teaching philosophy, and a list of three references, in a single PDF, to either **theoryphysics@binghamton.edu** or **computationalphysics@binghamton.edu** before **January 8th 2014**. These are affiliated positions for Smart Energy, which is one of five transdisciplinary areas of excellence (TAE) for growth under the auspices of the SUNY2020 plan. The search committee will include members of the Smart Energy steering committee. For more information on the SUNY2020 plan and the TAE programs, please visit **http:www.binghamton.edu/academics/provost/tae2013.html**. *Binghamton University is an affirmative action/equal opportunity employer. Members of minority groups and women are especially encouraged to apply.* C1113075

Experimental Condensed Matter Tenure-Track Assistant or Associate Professor Position
Department of Physics and Astronomy
University of Denver

The Department of Physics and Astronomy at the University of Denver underwent strong expansion with eight new tenure-track positions filled in the last seven years. New positions were filled in condensed matter physics, astrophysics, and biophysics. This announcement invites applications for a tenure-track position at the Assistant Professor or Associate Professor level in experimental condensed matter physics, including soft condensed matter and other related interdisciplinary research areas. The position will commence in September 2014. We are especially interested in candidates with research relevant to our involvement in the University's two interdisciplinary initiatives, the Center for Nanoscale Science and Engineering and the Molecular Life Science and Biophysics Program. The successful candidate will have a B.S. in physics and Ph.D. in physics or related discipline, will develop an extramurally funded research program, will supervise undergraduate and graduate research, and will teach undergraduate and graduate courses. Individuals with postdoctoral experience are particularly encouraged to apply. More information about the department can be found at http://www.physics.du.edu. The department offers degrees through the Ph.D. Applicants must apply through the website: http://www.du.edu/hr/employment/jobs.html. The application should include: a cover letter, curriculum vitae, statements of teaching philosophy and experience, proposed research program, and names of at least three references. The selection process will begin on **January 1, 2014**, and continue until the position is filled. *The University of Denver is committed to enhancing the diversity of its faculty and staff and encourages applications from women, minorities, people with disabilities, and veterans. The University is an equal opportunity/affirmative action employer. The department is particularly interested in candidates who have experience working with diverse populations and have knowledge of diverse pedagogical techniques and approaches. Applicants are requested to include in their application information about how they will advance diversity through their research, teaching and/or service.* C1113074

Assistant Professor – Accelerator Physics

The Department of Physics & Astronomy (http://physics.sunysb.edu/Physics/) at **Stony Brook University** invites applications for a tenure-track Assistant Professor faculty position in the field of Accelerator Physics. In some circumstances, a joint appointment with Brookhaven National Laboratory (BNL) may be considered. The expected start date is September 2014. The Department benefits from its highly ranked faculty in research and teaching, excellent students, and close affiliation with experimental and theoretical research centers of international reputation, and its proximity to BNL. We also host a Center for Accelerator Research and Education: a collaboration between Stony Brook and BNL since 2008. The successful candidate will have demonstrated research credentials in accelerator research, the ability to attract independent research funding and a keen interest in teaching undergraduate and graduate courses in the department. The applications should be submitted at: https://academicjobsonline.org/ajo/jobs/3330. Applications should include a cover letter, curriculum vitae, copies of up to three recent papers, a research statement, a statement of teaching philosophy, and names (and affiliation) of at least three references. The candidate should use the options provided at the WEB site to request the letters of references. The review of applications will start on **December 15, 2013**, but applications will be accepted until the position is filled. Electronic submission via academicjobsonline is strongly preferred. Alternatively, applicants may submit the application materials by mail to: **Nathan Leoce-Schappin, Assistant to the Chair, P-104 Physics Bldg., Stony Brook, NY 11794-3800**. For further information visit www.stonybrook.edu/jobs (Ref#: **F-8211-13-10**). *Stony Brook University/SUNY is an equal opportunity, affirmative action employer.* C1113078

University of Colorado (http://mse.colorado.edu/). The interdisciplinary Materials Science and Engineering program at the University of Colorado seeks to hire three exceptional candidates as **tenure-track assistant professors.** This program offers tenure-track appointments in science and engineering departments across the campus to candidates with interests in materials research. Candidates with interests in all materials research areas will be considered. Application materials are accepted electronically at https://www.jobsatcu.com, posting number **F00773**. Review of applications will begin **October 31, 2013** and will continue until the positions are filled. The openings are targeted at the level of Assistant Professor, but experienced candidates with outstanding credentials may be considered for Associate or Full Professor. *The University of Colorado Boulder is an Equal Opportunity/Affirmative Action employer. The University of Colorado Boulder conducts background checks for all final applicants.* C1113071

Research Associate in Theoretical Nuclear Physics/Astrophysics
University of Minnesota

The Nuclear Theory Group at the University of Minnesota expects to have a postdoctoral Research Associate position available beginning in fall of 2014. A Ph.D. in physics, astronomy, or the equivalent is required by the date of appointment. The permanent group members are Joseph Kapusta and Yong Qian. Their current research interests include heavy ion collisions at RHIC and LHC, AdS/QCD, finite temperature field theory, neutron stars, neutrino astrophysics, supernova explosions and gamma-ray bursts, evolution and nucleosynthesis of massive stars, and chemical evolution of galaxies. Appointments are made for one year and normally are renewable for a second, subject to funding and performance. The application, including a cover letter, CV, and list of references must be completed on-line. Applicants for this position must go to https://employment.umn.edu/applicants/Central?quickFind=115432. In addition, three letters of recommendation should be sent by email to jjmurphy@physics.umn.edu (preferred) or by postal mail to arrive by **January 15, 2014** to: **Professor Yong-Zhong Qian, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.** Review of applications will begin **December 1, 2013** and continue until the position is filled. For inquiries please contact **Professor Yong-Zhong Qian**. *The University of Minnesota is an equal opportunity educator and employer.* C1113070

Condensed Matter Theory Faculty Position
Department of Physics and Astronomy
Johns Hopkins University

The Department of Physics and Astronomy of the Johns Hopkins University expects to fill a tenure-track or tenured faculty position in theoretical condensed matter physics. This is an open-rank search, and candidates will be considered for appointment both at the assistant professor level and at higher ranks, as appropriate. The successful candidates will be expected to maintain active research programs in any area of soft or hard condensed matter physics and to teach at both the undergraduate and graduate levels. Applicants should submit a curriculum vitae, a list of publications, and short description of research plans via Interfolio to https://apply.interfolio.com/23600. Applicants who wish to be considered at the level of assistant professor should have three letters of recommendation submitted on their behalf to the same address. If you have questions concerning Interfolio, please call **(887) 997-8807** or email help@interfolio.com. You may also contact **Pam Carmen** at **(410) 516-7346** or pam@pha.jhu.edu. Consideration of applications will begin on **January 1, 2014**, and will continue until the positions are filled. *Johns Hopkins University is an affirmative action/equal opportunity employer, and welcomes applications from women and members of underrepresented groups.* C113099

ADJUNCT PROFESSOR OF APPLIED AND COMPUTATIONAL PHYSICS

The Department of Physics at **Oakland University** is seeking an outstanding physics instructor for the position of Full-Time Adjunct Professor of Applied and Computational Physics, starting on August 15, 2014. Candidates should have experience teaching physics at all levels, from large introductory classes to core classes for undergraduate physics majors to graduate level classes. The ability to teach both computational physics (we plan to establish a new PhD program in Applied and Computational Physics) and medical physics (we have an existing Medical Physics PhD program) are required. Research expertise and ability to supervise undergraduate student research in an area of strength in the department (medical physics, condensed matter physics, and gravitational physics) is expected. For further information about the department, see www.oakland.edu/physics. Applicants should submit a curriculum vitae, a statement of teaching philosophy and experience, and a description of research interests to http://academicjobs.oakland.edu/postings/807, and arrange for three letters of reference to be sent to: **The Search Committee, Department of Physics, Oakland University, Rochester, MI 48309,** or by email (preferred) to physics@oakland.edu. Address any questions to Brad Roth, search committee chair (roth@oakland.edu). To receive full consideration, applications should be received by **December 1, 2013**. *Oakland University is an Equal Opportunity/Affirmative Action Employer. Women and Minorities are encouraged to apply.* C113092

Seeking Observational Astronomer/Astronomy Educator AS-0022-13

The Department of Physics at **Boise State University** seeks an observational astronomer with a passion for, and record of success in, teaching and public outreach for a tenure-track position at the Assistant Professor level, starting August 2014. A B.S. degree in Physics and a Ph.D. degree in Astronomy (observational) or Astronomy Education are strongly preferred. The successful candidate must be able to develop an externally funded research program, preferably in observational astronomy, that engages undergraduates. Of equal importance is the ability to be an exceptional teacher, inspire and mentor students, and engage the public in astronomy related outreach programs. Excellent spoken and written communication skills are a must. See www.boisestate.edu/physics for more details. Please e-mail a cover letter, CV, detailed research plans, a summary of teaching experience and philosophy, a list of goals and plans for community outreach and the recruitment of new physics majors, plus contact information for 3 references, to physics@boisestate.edu, with the subject line "**Observational Astronomer**." Review of applications will begin **January 10, 2014**, and will continue until a qualified applicant pool is identified. *Boise State University and the Physics Department are strongly committed to achieving excellence through cultural diversity. Applications from women and minorities are strongly encouraged. Boise State University is an EOE/AA employer.* C113079

The Department of Chemistry and Physics at **Georgia Regents University** (www.gru.edu) invites applications for one (and pending approval, two) tenure track **Assistant Professor of Physics** positions to begin Fall 2014. We seek physicists with a strong commitment to undergraduate education which includes teaching lower- and upper-division courses and labs, advising and mentoring students, establishing and maintaining a research program that meaningfully engages undergraduate students, and participating in service activities. Applications from candidates with research expertise in theoretical condensed matter physics, seismology, or biophysics are encouraged to apply, especially those with computational background. Applicants must have a Ph. D. in physics with an excellent record of scholarly activity that demonstrates an ability to develop a research program independently. Postdoctoral experience is preferred but not required. GRU was formed by the Board of Regents of Georgia by consolidating Georgia Health Sciences University with Augusta State University to become the fourth comprehensive research university in the state of Georgia. The department anticipates adding graduate programs in the future. To apply, complete application form at www.gru.edu/jobs/external.php (faculty position **11628**) and submit a cover letter addressing interest in GRU, CV, teaching statement that describes your experience with, and commitment to, undergraduate physics education, research statement outlining future research plans and clear goals on how to involve undergraduates in research with potential for external funding. Arrange for transcripts and three letters of recommendation. Send materials to: **Physics Search; SCI W3005; Georgia Regents University; 1120 15th St.; Augusta, GA 30912** or nbourne@gru.edu. Application deadline: **December 1, 2013**. *GRU is an Equal Opportunity Employer.* C113083

FACULTY POSITION IN DATA INTENSIVE ASTROPHYSICS

The Department of Physics & Astronomy at **The Johns Hopkins University** seeks to fill an approved faculty position in the field of data intensive astrophysics. It is expected that the new faculty member would advance data intensive science and its application to astrophysics. The Department has been a leader in data intensive astrophysics and aims to expand its expertise in this rapidly developing field. The Department has specialized in large astronomical surveys, most recently including SDSS III & IV, Pan-STARRS1, Subaru Prime Focus Spectrograph, Euclid, LSST, and WFIRST. The new faculty member may join these efforts and/or identify new opportunities. This new position is part of a major campus-wide investment in data intensive science and engineering. As such, the new faculty member in our Department would also be a part of JHU's interdisciplinary Institute for Data Intensive Science and Engineering (IDIES) to enhance cross-disciplinary communication and collaboration on "big data" techniques and methodologies as a means to stimulate major advances. We anticipate that the position is to be filled at the level of tenure-track Assistant Professor or tenured Associate Professor. Applicants should submit a curriculum vitae, a list of publications, and short description of research plans via Interfolio to https://apply.interfolio.com/23601. Applicants who wish to be considered at the level of assistant professor should also arrange to have three letters of recommendation submitted on their behalf to the same address. If you have questions concerning Interfolio, please call **(887) 997-880** or email help@interfolio.com. You may also contact **Pam Carmen** at **(410) 516-7346** or pam@pha.jhu.edu. Consideration of applications will begin on **January 1, 2014**, and will continue until the positions are filled. *Johns Hopkins University is an affirmative action/equal opportunity employer, and welcomes applications from women and members of underrepresented groups.* C113098

Assistant or Associate Professor
Physics

The South Dakota School of Mines and Technology Physics Department invites applications for a tenure-track **Assistant** or **Associate Professor** position in experimental particle physics, nuclear physics, or nuclear astrophysics. The School of Mines has a close working relationship with the Sanford Underground Research Facility (SURF) in Lead, South Dakota. Our department has established a new Ph.D. program in physics and intends to develop strong research programs in neutrino physics, direct detection of dark matter, proton decay, and related areas that require deep underground shielding and a low-background environment. SURF is a host or potential host of several underground experiments such as LBNE, LUX/LZ, MAJORANA DEMONSTRATOR and DIANA. We primarily seek candidates at the Assistant Professor level; however exceptional candidates with a proven track record of success in obtaining external funding may be considered for an Associate Professor position. Applicants must have a Ph.D. in nuclear/particle physics or a related field. Successful candidates are expected to build strong externally funded research programs, supervise graduate students, and teach at the undergraduate and graduate levels. They will also participate in the full range of faculty responsibilities, including academic advising, service on committees, sustained scholarly research, and outreach activities. Postdoctoral research experience is highly desirable. The anticipated start date is August 22, 2014. The School of Mines is committed to recruiting and retaining a diverse workforce and offers an excellent comprehensive benefits package including paid medical and life insurance for our employees, as well as medical, dental and vision coverage for spouses and dependents; retirement plans; paid holidays; and a generous sick day allowance. Individuals interested in this position must apply online at http://www.sdsmt.edu/employment. Human Resources can provide accommodation to the online application process and may be reached at **(605) 394-1203**. Review of applications will begin **January 15, 2014,** and will continue until the position is filled. Employment is contingent upon completion of a satisfactory background investigation. For more information about the School of Mines and Rapid City, visit: www.sdsmt.edu and http://visitrapidcity.com/. *SDSM&T is an EEO/AA/ADA employer & provider.* C113090

Associate or Professor
Physics

The South Dakota School of Mines and Technology Physics Department invites applications for a **tenure-track senior faculty position** in experimental particle physics, nuclear physics, or nuclear astrophysics. The School of Mines has a close working relationship with the Sanford Underground Research Facility (SURF) in Lead, South Dakota. Our department has established a new Ph.D. program in physics and intends to develop strong research programs in neutrino physics, direct detection of dark matter, proton decay, and related areas that require deep underground shielding and a low-background environment. SURF is a host or potential host of several underground experiments such as LBNE, LUX/LZ, MAJORANA DEMONSTRATOR and DIANA. We seek candidates with a proven track record of success in obtaining external funding. The appointment will be made at the Associate Professor level; however exceptional candidates will be considered at the level of a Full Professor. Applicants must have a Ph.D. in nuclear/particle physics or related fields. The successful candidate is expected to build strong externally funded research programs and lead a departmental effort in particle and nuclear physics. He or she will also supervise graduate students and postdoctoral scientists, teach at the undergraduate and graduate levels, and assume the usual duties of senior faculty. Previous leadership experience with large particle or nuclear physics collaborations, including securing and managing NSF and/or DOE grants, is highly preferable. The anticipated start date is August 22, 2014. The School of Mines is committed to recruiting and retaining a diverse workforce and offers an excellent comprehensive benefits package including paid medical and life insurance for our employees, as well as medical, dental and vision coverage for spouses and dependents; retirement plans; paid holidays; and a generous sick day allowance. Individuals interested in this position must apply online at http://www.sdsmt.edu/employment. Human Resources can provide accommodation to the online application process and may be reached at **(605) 394-1203**. Review of applications will begin **January 15, 2014**, and will continue until the position is filled. Employment is contingent upon completion of a satisfactory background investigation. For more information about the School of Mines and Rapid City, visit: www.sdsmt.edu and http://visitrapidcity.com/. *SDSM&T is an EEO/AA/ADA employer & provider.* C113091

TENURE TRACK FACULTY POSITION IN EXPERIMENTAL PARTICLE PHYSICS
MICHIGAN STATE UNIVERSITY

The Department of Physics and Astronomy is seeking outstanding candidates to fill a tenure-track position at the assistant professor level in Experimental Particle Physics. Candidates are expected to hold a Ph.D. in physics and have completed at least one successful post doctoral assignment. Candidates must exhibit unusually high promise for excellence in both research and teaching and be an expert in particle physics research in the "Intensity Frontier" or the "Cosmic Frontier." We are especially interested in particle physicists with technical capabilities and interests in electronics, detector design, or a joint program with accelerator R&D. The High Energy Group at MSU consists of seven experimental and seven theoretical physics faculty. We have long-standing programs at the DØ, CDF, ATLAS, HAWC, and NOvA experiments. MSU is also the home of CTEQ and we enjoy close collaboration between experiment and theory. We have outstanding electronics engineering, mechanical shops, and computing facilities, and we enjoy a devoted high-bay laboratory for particle physics projects. We are seeking to expand existing efforts or start a new one. Applications should be uploaded to MSU's online job application site, http://jobs.msu.edu with reference to posting #8481. They should include a cover letter, CV, a one-page teaching statement, and a statement of research plans. Letters of reference from three individuals are required and referees should be guided to the above site to upload their letters. Questions should be directed to **Prof. Raymond Brock, Chair of the HEP Search Committee, Department of Physics and Astronomy, Michigan State University, Biomedical Physical Sciences, 567 Wilson Road, Room 3210, East Lansing, MI 48824, USA.** Consideration of applications will commence **November 30, 2013** and will continue until the position is filled. *MSU is committed to achieving excellence through cultural diversity. The University actively encourages applications of women, persons of color, veterans, and persons with disabilities. MSU endeavors to facilitate employment assistance to spouses or partners of candidates for faculty and academic staff positions. Michigan State University is an affirmative-action, equal-opportunity employer.* CI113051

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
FACULTY POSITIONS

The Department of Electrical Engineering and Computer Science (EECS) seeks candidates for faculty positions starting in September 2014. Appointment will be at the assistant or untenured associate professor level. In special cases, a senior faculty appointment may be possible. Faculty duties include teaching at the undergraduate and graduate levels, advising students, conducting original scholarly research, supervising student research, and developing course materials at the graduate and undergraduate levels. We will consider candidates with backgrounds and interests in any area of electrical engineering and computer science. Faculty appointments will commence after completion of a doctoral degree. Candidates must register with the EECS search website at **https://eecs-search.eecs.mit.edu**, and must submit application materials electronically to this website. Candidate applications should include a description of professional interests and goals in both teaching and research. Each application should include a curriculum vita and the names and addresses of three or more individuals who will provide letters of recommendation. Letter writers should submit their letters directly to MIT, preferably on the website or by mailing to the address below. Please submit a complete application by **December 1, 2013**. Send all materials not submitted on the website to: **Professor Anantha Chandrakasan, Department Head, Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Room 38-401, 77 Massachusetts Avenue, Cambridge, MA 02139.** *M.I.T. is an equal opportunity/affirmative action employer.* CI113060

TENURE TRACK ASSISTANT PROFESSOR
Department of Physics, Central Washington University

The Department of Physics at Central Washington University invites applications for a full-time, tenure-track Assistant Professor position beginning September 16, 2014. The principal responsibilities of tenure-track physics faculty at CWU are teaching lower- and upper-division courses, advising and mentoring students, establishing and maintaining a research program that meaningfully engages undergraduate students, and participating in service activities. The CWU physics department has quadrupled the number of majors over the past seven years, largely due to award-winning, student-centered faculty, innovative curricula, and a long-term commitment to implementing recommendations of the AAPT SPIN-UP report. A new, state-of-the-art facility to house the department is scheduled for occupancy in 2015. The department delivers two bachelor degree programs, as well as service and general education courses, in a department culture that is highly collegial and supportive. A full-time instructional technician with a well-equipped shop supports the faculty. The department also hosts an exceptionally active, award-winning Society of Physics Students chapter and astronomy club. The current academic interests of faculty members include FIR spectroscopy, optics, acoustics, astronomy, and science education. Applicants must have a Ph. D. in physics or a closely related field and a record of scholarly activity that demonstrates an ability to develop a research program that can meaningfully engage undergraduate students. Preferred qualifications include experience using active learning techniques to teach physics and successful grant writing experience. Candidates with a research focus in biophysics will receive special attention, although applications from candidates with other specialties are also welcome. Application must be submitted electronically at **http://jobs.cwu.edu/postings/4377**. Screening will begin on **December 1, 2013** and continue until a candidate is selected. A complete application consists of 1) a cover letter that summarizes the qualifications identified in this position announcement, including a statement describing how the applicant can contribute to the department's implementation of the AAPT SPIN-UP report; 2) a teaching statement that describes the applicant's experience with, and commitment to, undergraduate physics education; 3) a statement that describes a plan for implementing a research program that includes meaningful participation by undergraduate students with potential for external funding; 4) a current vita; 5) the names, addresses, e-mail and telephone numbers of three professional references. Do not send reference letters; they will be solicited for finalists. *As an AA/EEO/Title IV Institution, Central Washington University is dedicated to the goal of building a culturally diverse faculty committed to teaching and working in a multicultural environment. We actively encourage applications from all those who can contribute to the diversity and excellence of the academic community at Central Washington University.* CI113067

PHYSICS. Westminster College, New Wilmington, Pennsylvania. The Department of Physics at Westminster College invites applications for a **tenure-track position** starting in fall 2014. A Ph.D. in physics or a related field is required. Applicants must be committed to excellence in teaching, both within the physics major and within the College's liberal arts curriculum. The typical teaching load is two courses and two labs per semester. Applicants must also be committed to establishing an experimental or computational research program that includes opportunities for the participation of undergraduate students. Start-up funds are available. Westminster College is a coeducational, national liberal arts institution with historical ties to the Presbyterian Church (USA). The College enrolls approximately 1,400 full-time undergraduate students and employs approximately 104 full-time faculty. It is located in rural western Pennsylvania and is within easy driving distance of both Pittsburgh and Cleveland. Applicants should send statements describing teaching philosophy and research interests, a CV and three letters of recommendation to **Dr. Craig L. Caylor, Department of Physics, Westminster College, New Wilmington, PA 16172-0001**, or by email to caylorcl@westminster.edu. Application review will begin **January 13, 2014**. Applications will be accepted until an appointment is made. *EOE.* CI113100

ADDRESS CHANGES

Members of AIP Physics Societies

Members of the physics societies listed below should contact their societies to change mailing address or e-mail or to report missing copies, inquire about their membership status, etc. Detailed instructions about changing address follow:

AAPM
www.aapm.org/memb click on "View your member profile" and follow the prompts.

AAPT
http://www.aapt.org/Membership/myaccount.cfm and click on "My Profile"

AAS
https://members.aas.org/services/aas_member, click on "Change of Address"

ACA
Send an e-mail to aca@hwi.buffalo.edu. Include name, old and new address.

APS
Send an e-mail to coa@aps.org with membership #, old and new address, go to http://www.aps.org/membership and click on "My Member Profile"

ASA
Send an e-mail to asamembership@aip.org with the membership #, old address and new address, or login to update your profile at www.associationsciences.org/asa/

AVS
https://www.avs.org/Login, enter username and password, and select "Update profile".

OSA
http://account.osa.org, click on "Contact Information" update your address.

SOR
Send an e-mail to membership@aip.org with the membership #, old address and new address, or log in at http://www.rheology.org/sormbr

SPS
Send an email to spsmembership@aip.org with the membership #, old address and new address.

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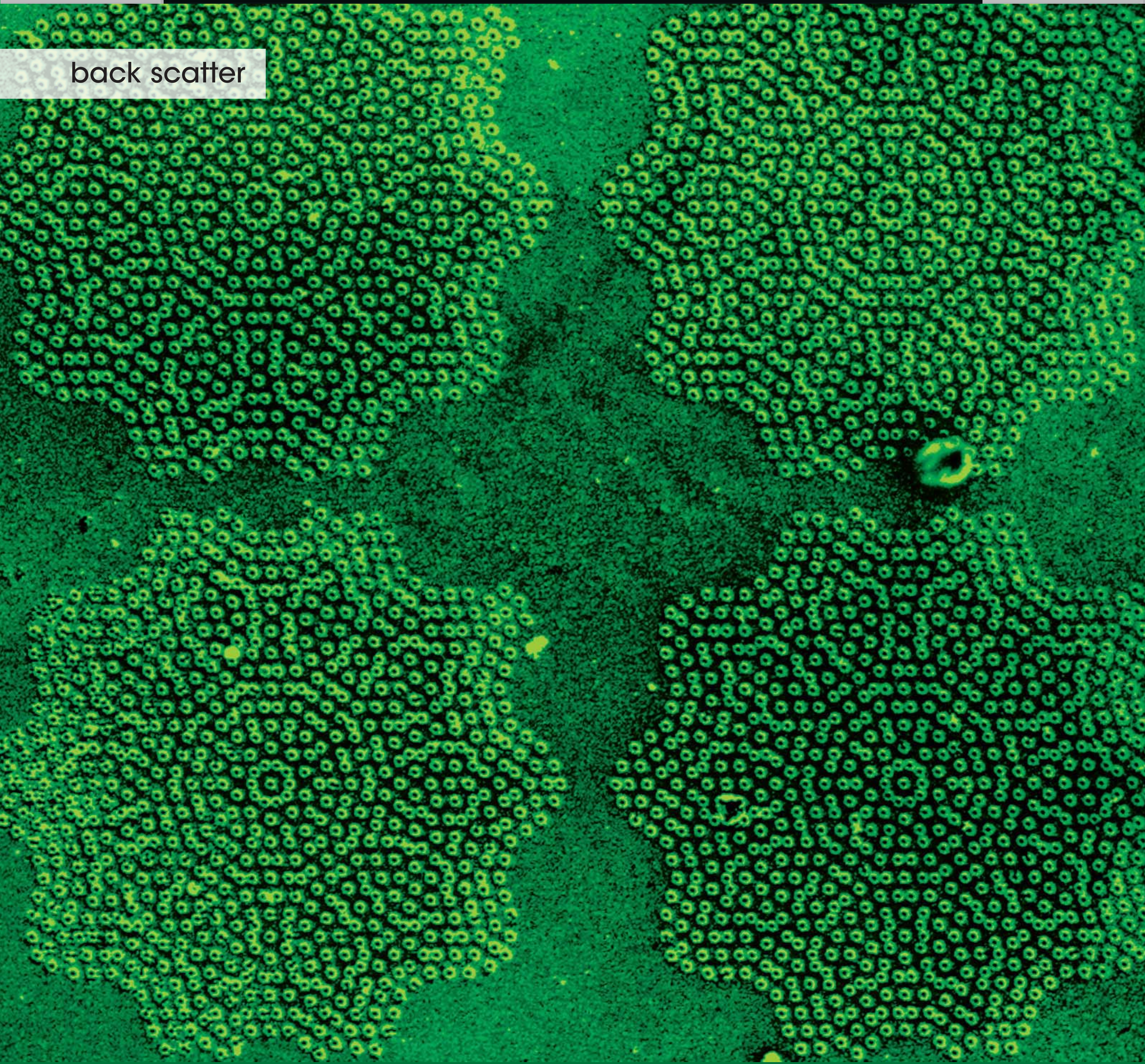

Magnetic molds

Bartosz Grzybowski and colleagues at Northwestern University have demonstrated a new technique for precisely assembling colloidal particles into complex two- and three-dimensional arrangements. The process begins with a template: The researchers used photolithography to fabricate a pattern of nickel islands, 1–10 microns in diameter and 200 nanometers thick, and embedded the islands in a layer of silicone to create a flat surface. They then placed the template on a 0.4-tesla permanent magnet and underneath a solution of colloidal particles in a paramagnetic holmium nitrate solution. Because nickel has a large magnetic susceptibility, the template modulates and concentrates the magnet's otherwise uniform field. The resulting microgradients in the fluid form a magnetic mold that draws paramagnetic particles onto the islands and pushes diamagnetic particles into the gaps between the islands. If desired, the particles can be configured to bond together, so that the structure remains even after the magnet is removed.

This scanning electron micrograph shows quasicrystalline assemblies of nonmagnetic silica beads created with a magnetic mold. For a wide variety of templates and colloids, the team reports fidelity greater than 80%. The process has great versatility: Not only can one adjust the shape of the islands and their relative size with respect to the colloidal particles, but since the gradients extend vertically into the fluid, the molds can assemble particles into 3D clusters. The team even created colonies of bacteria. (A. F. Demirörs et al., *Nature*, in press. Image by Ahmet Demirörs.)

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